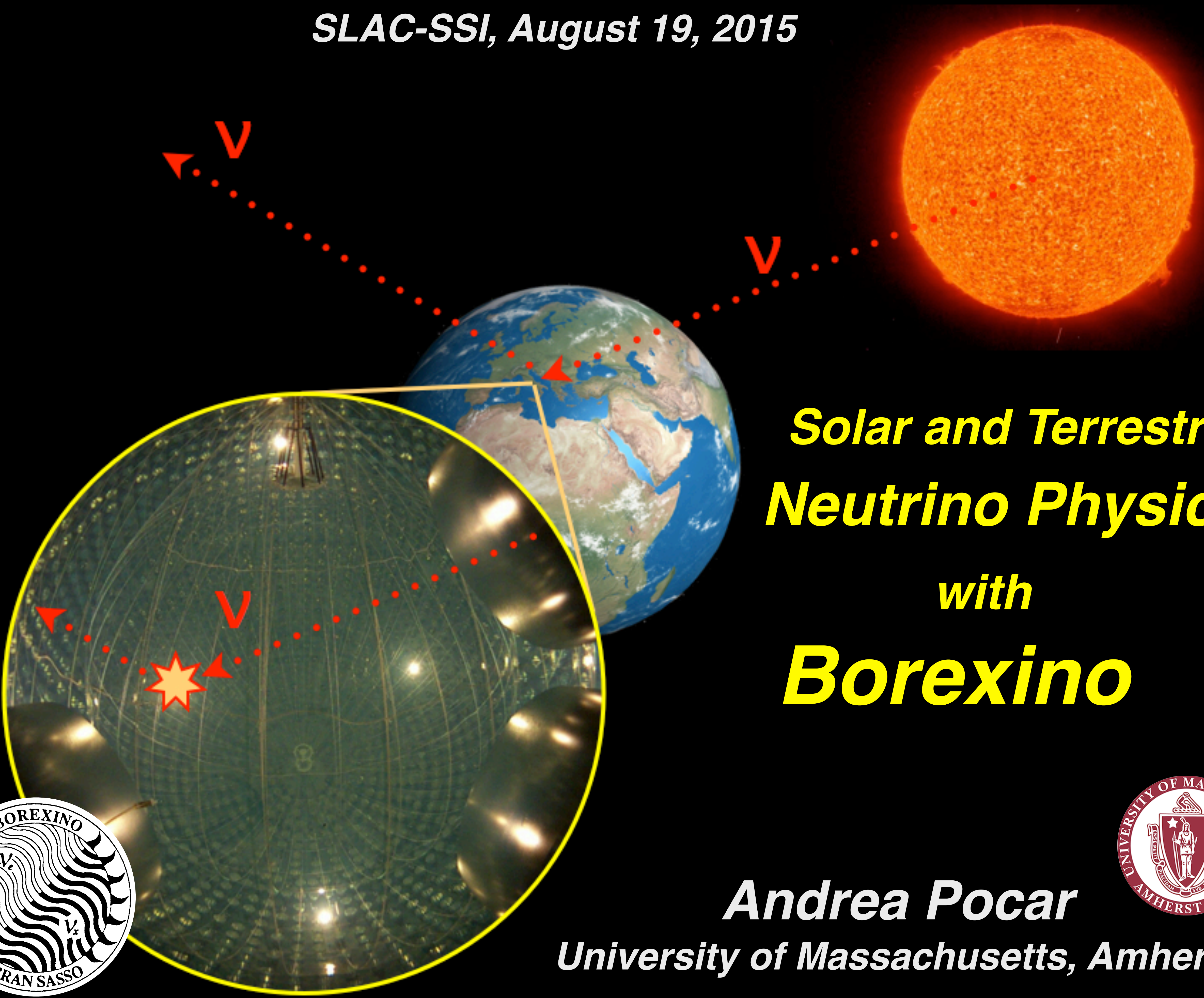
SLAC-SSI, August 19, 2015



Solar and Terrestrial Neutrino Physics with Borexino

Andrea Pocar

University of Massachusetts, Amherst

Outline

- Neutrinos - historical perspective

- Solar neutrinos
    - *fusion processes in the Sun*
    - *the solar neutrino puzzle*

- The Borexino project
    - *the beginnings, science drivers*
    - *the detector and challenges*
    - *main results*
    - *most recent results: pp solar neutrinos, geoneutrinos*

- Outlook

Neutrinos

- Fundamental particles that come in three flavors (e,μ,τ)
- Weakly interacting, spin 1/2, assumed to be massless until recently

- Linked to key discoveries in particle physics:
    - *Understanding of beta decay ('30)*
    - *Early theory of weak interactions ('34)*
    - *Solar energy generation via nuclear fusion ('37-'39, '58, ca.'70)*
    - *Parity violation ('56, '57)*
    - *Neutrino flavor oscillations ('98, '02, -->present)*
    - *Heat budget of the Earth ('05, -->present)*

- Current research includes: precision EW physics, neutrino mass, sterile neutrinos, Majorana fermions, dark matter

Neutrino sources

- Nuclear weapons (!)
  - Nuclear reactors
    - (people)
      - Accelerators
        - The Earth
          - The Sun
            - Supernovae
              - Big Bang

- Mean free path of neutrinos from a reactor in lead is ~ 0.3 light years

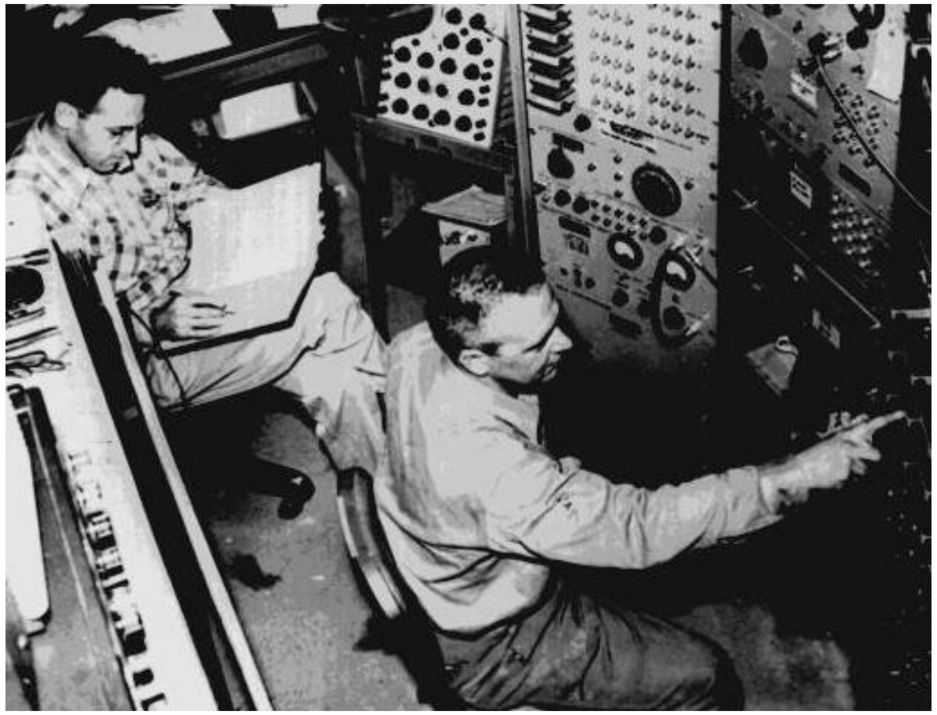
- A big nuclear reactor makes 6×10^{20} neutrinos/s: 20 meters away (just outside the building) only one neutrino every 3 sec interacts with our body

Bethe & Peierls 1934:
"… this implies that one evidently never will be able to detect Neutrinos."

First neutrino direct detection - 1956

First direct (anti)neutrino detection via inverse β-decay of the proton

(Reines and Cowan, Savannah River reactor)



Coincidence event:

prompt

$$\bar{\nu}_e + p \rightarrow n + e^+$$

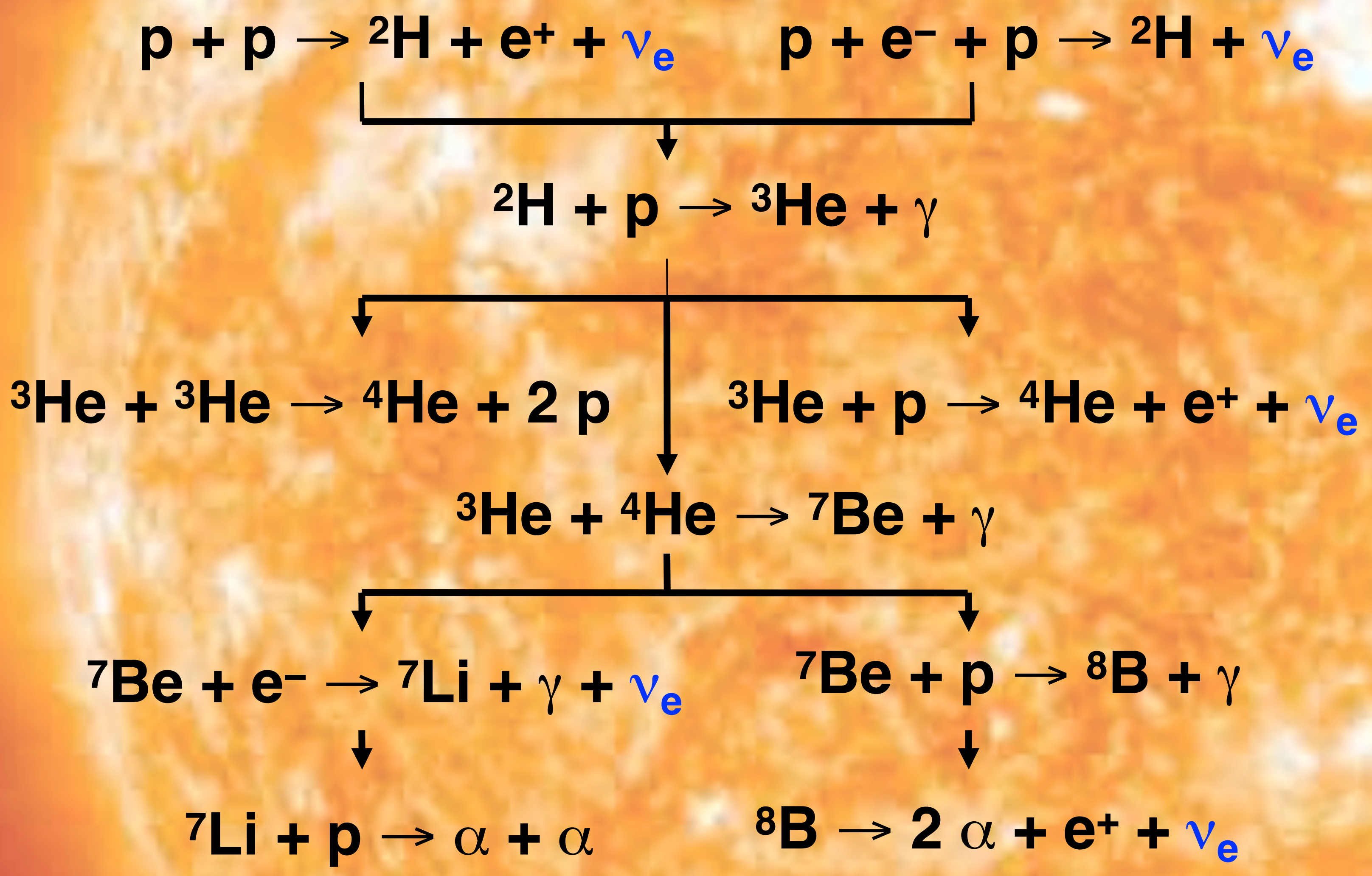
(E_{th} = 1.8 MeV)

delayed neutron capture with 2.2 MeV photon emission

the use of coincidences allowed to greatly enhance the signal over the 'singles rate' of the detector

Solar Fusion Reactions

p-p Solar Fusion Chain



$p + p \rightarrow {}^2H + e^+ + \nu_e$ $\quad$ $p + e^- + p \rightarrow {}^2H + \nu_e$

${}^2H + p \rightarrow {}^3He + \gamma$

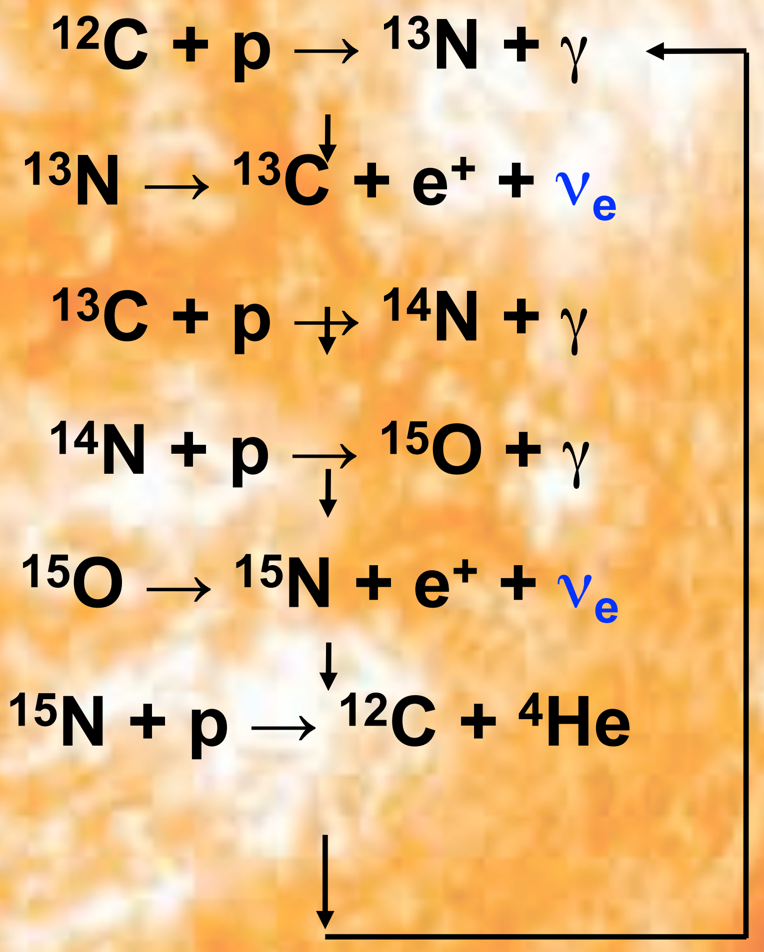
${}^3He + {}^3He \rightarrow {}^4He + 2\,p$ $\quad$ ${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$ $\quad$ ${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow \alpha + \alpha$ $\quad$ ${}^8B \rightarrow 2\,\alpha + e^+ + \nu_e$

CNO Solar Fusion Cycle



${}^{12}C + p \rightarrow {}^{13}N + \gamma$

${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$

${}^{13}C + p \rightarrow {}^{14}N + \gamma$

${}^{14}N + p \rightarrow {}^{15}O + \gamma$

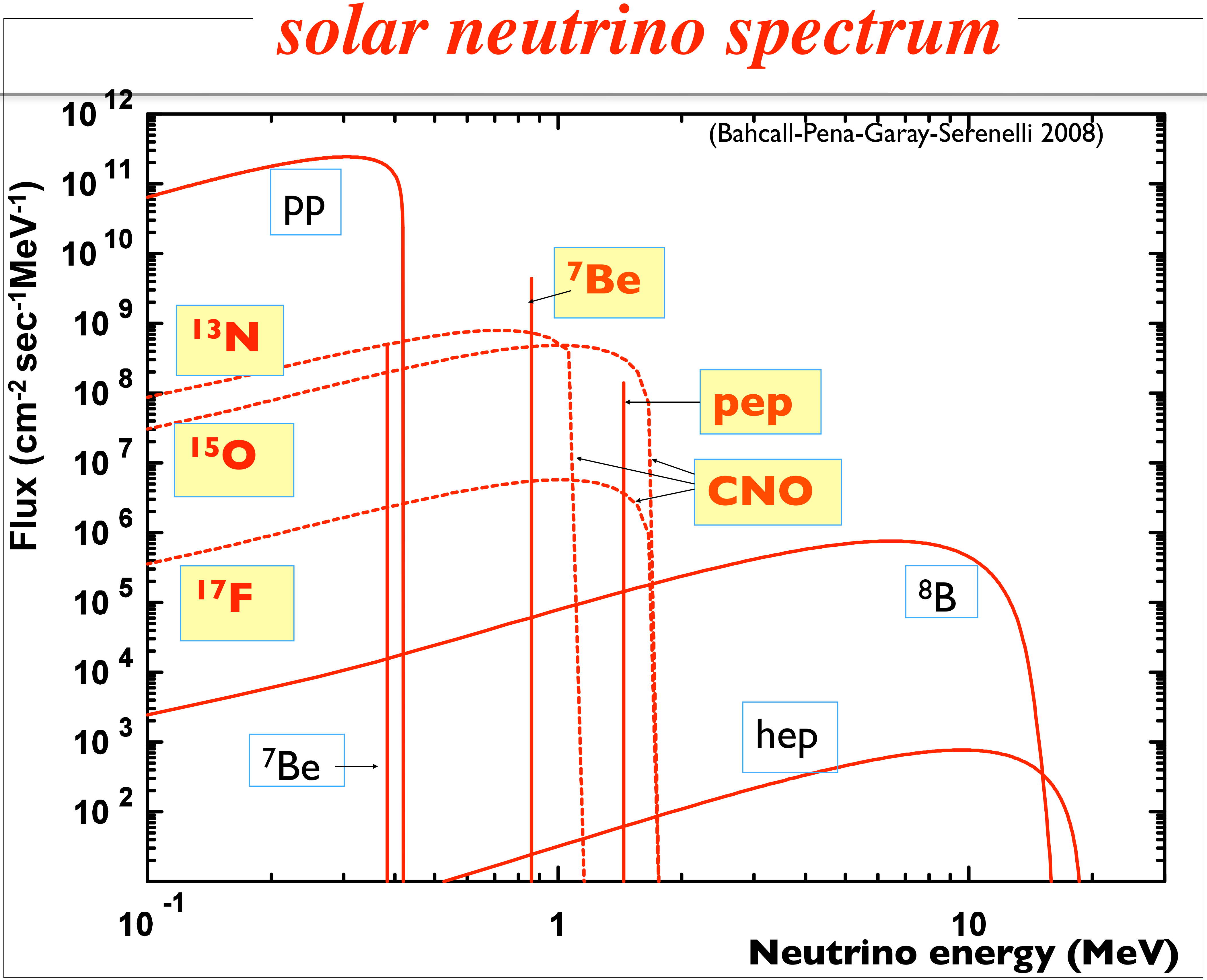
${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$

${}^{15}N + p \rightarrow {}^{12}C + {}^4He$

$$\boxed{4p \longrightarrow \mathrm{He}^4 + 2e^+ + 2\nu_e + 26.7\mathrm{MeV}}$$

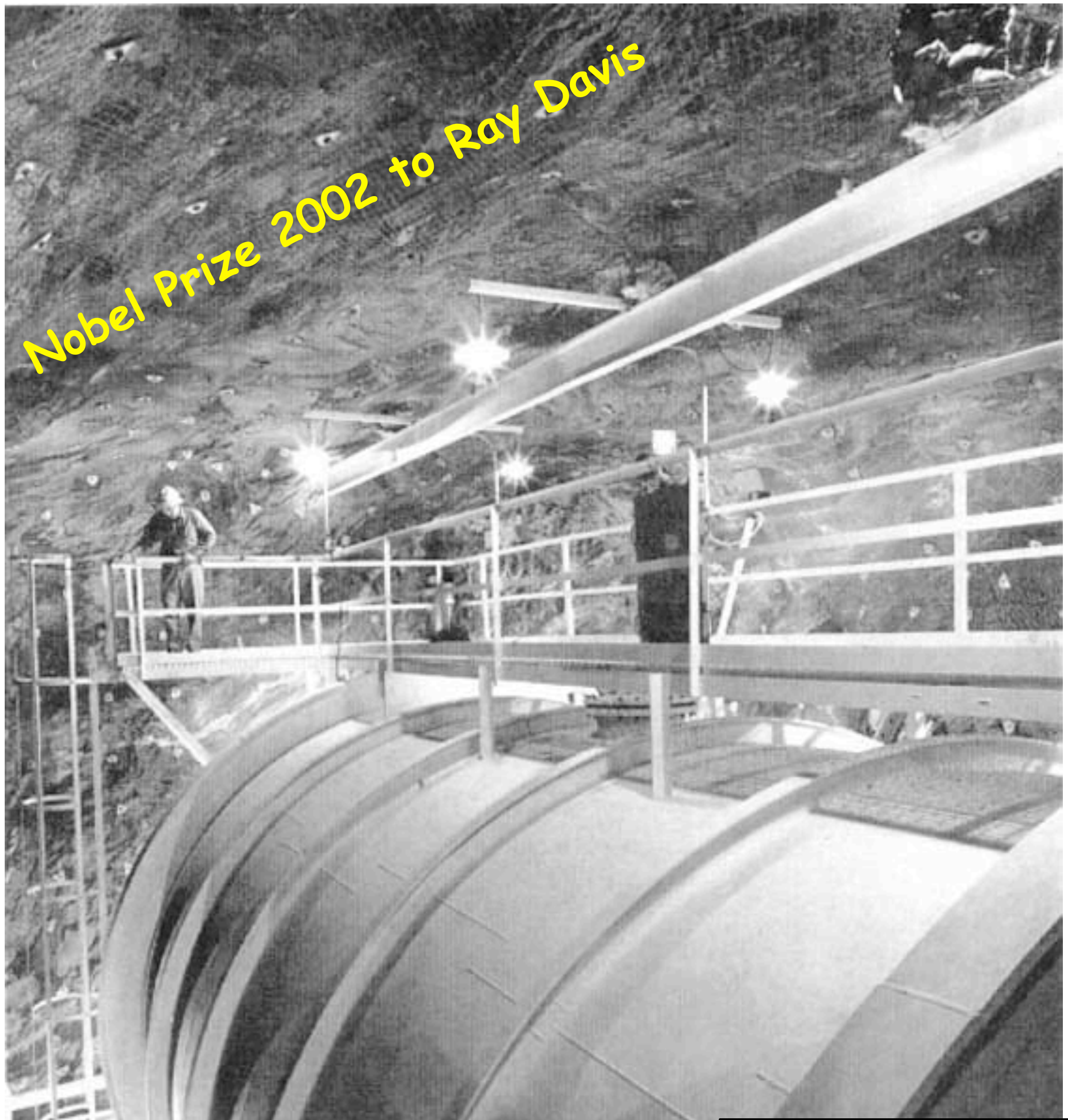
Image: bbc.co.uk

solar neutrino spectrum



BPS08: (Bahcall) Pena−Garay, C., & Serenelli, A. 2008, arXiv:0811.2424
Lower preferred heavy metal content (metallicity) decreased ^{7}Be by ~10%.
See also A. Serenelli, S. Basu, J. Ferguson, M. Asplund, arXiv:0909.26668v2

Solar neutrino detection



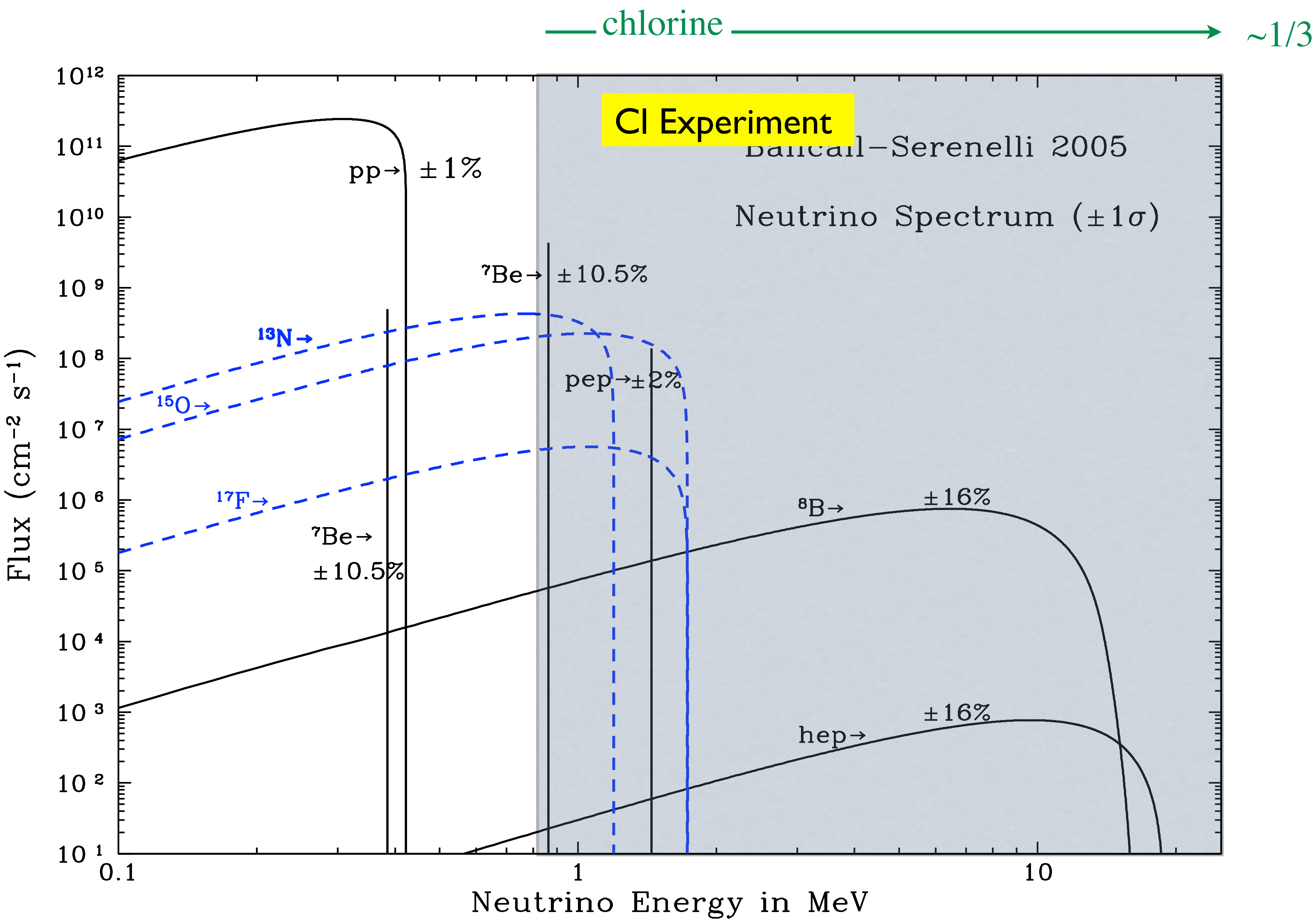
- Homestake Mine, Lead SD, 1400 m underground
- 615 tons of perchloroethylene (C_2Cl_4)

- **Cl-37 + ν --> Ar-37***
- ~ one ^{37}Ar atom produced every 2 days !

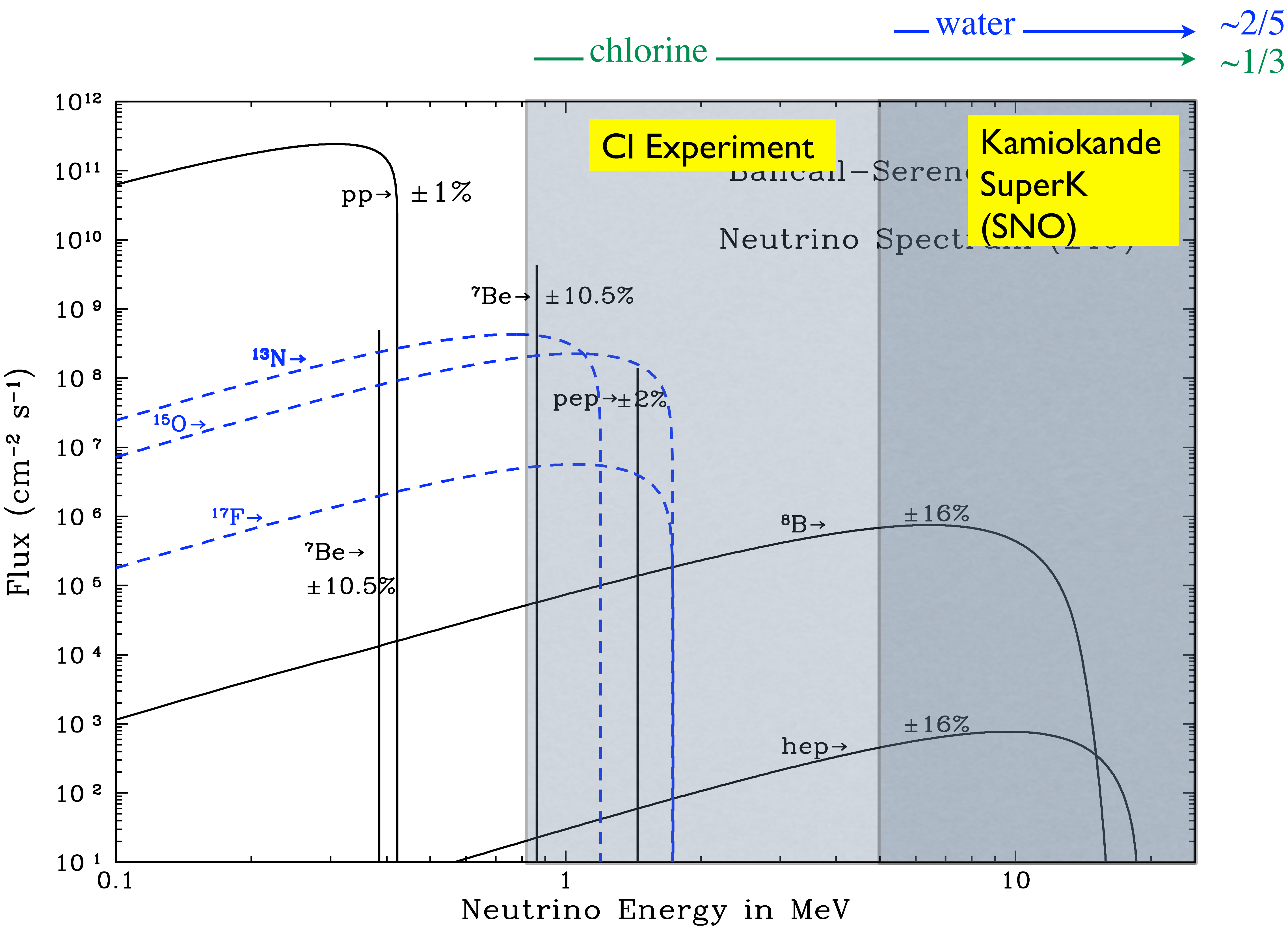
solar neutrino detection proves that there are fusion reactions in the sun

but:
observed only ~1/3 of the expected flux

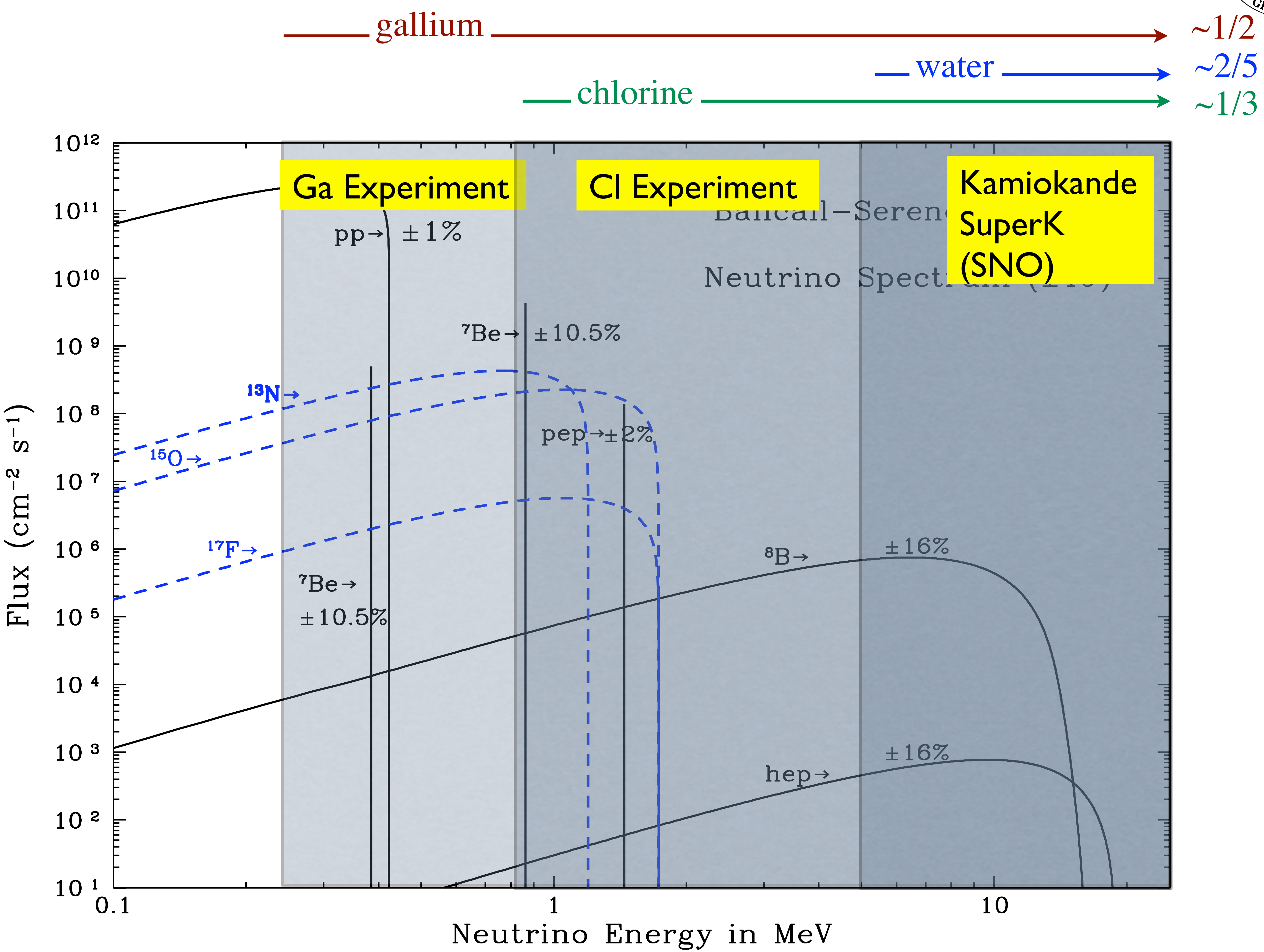
The Solar Neutrino "Puzzle"



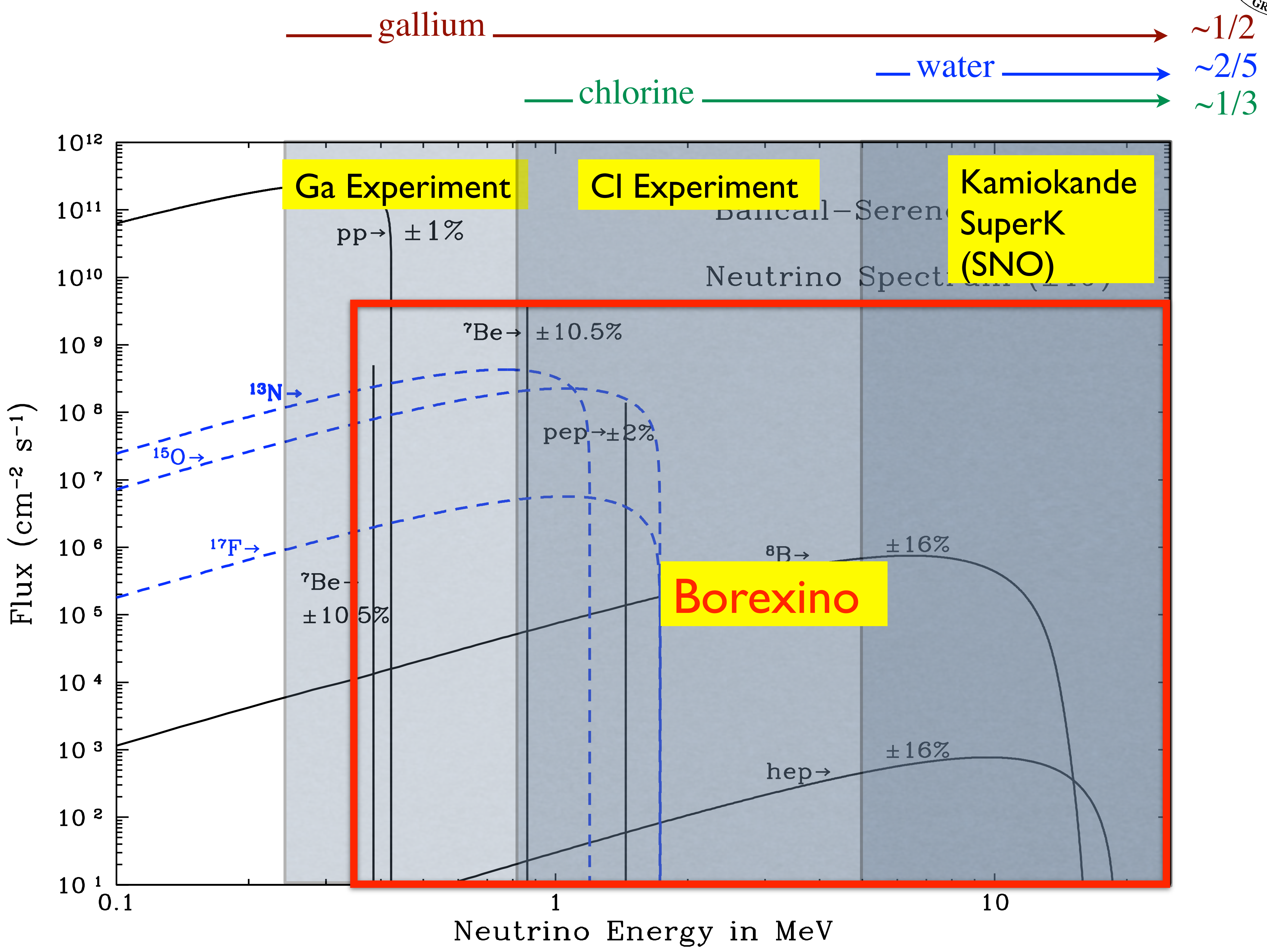
The Solar Neutrino "Puzzle"



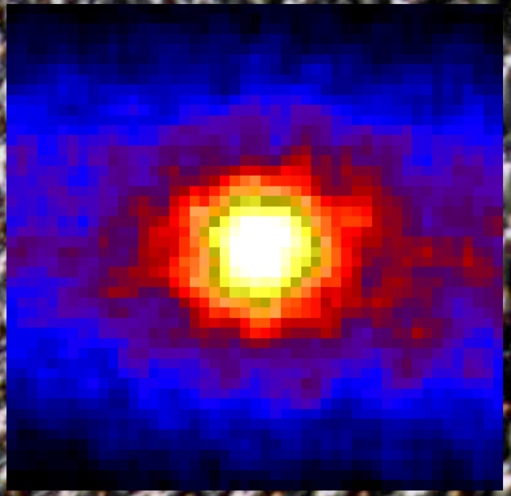
The Solar Neutrino “Puzzle”



The Solar Neutrino “Puzzle”



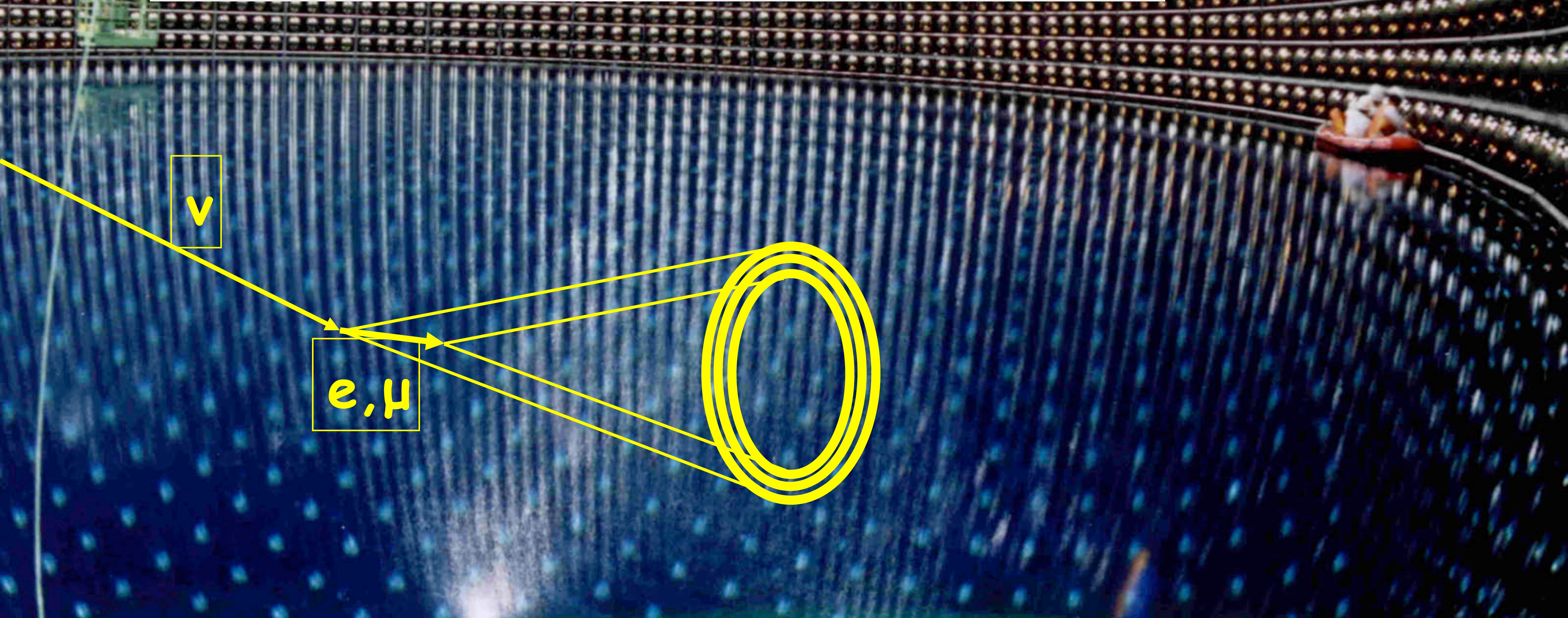
neutrinos oscillate!



1998: the SuperKamiokande experiment reports a deficit of muon-neutrinos is particle showers produced by cosmic rays in the upper atmosphere, evidence that $\nu_\mu \rightarrow \nu_\tau$

$$\pi \rightarrow \mu + \nu_\mu$$
$$\rightarrow e + \nu_e + \nu_\mu$$

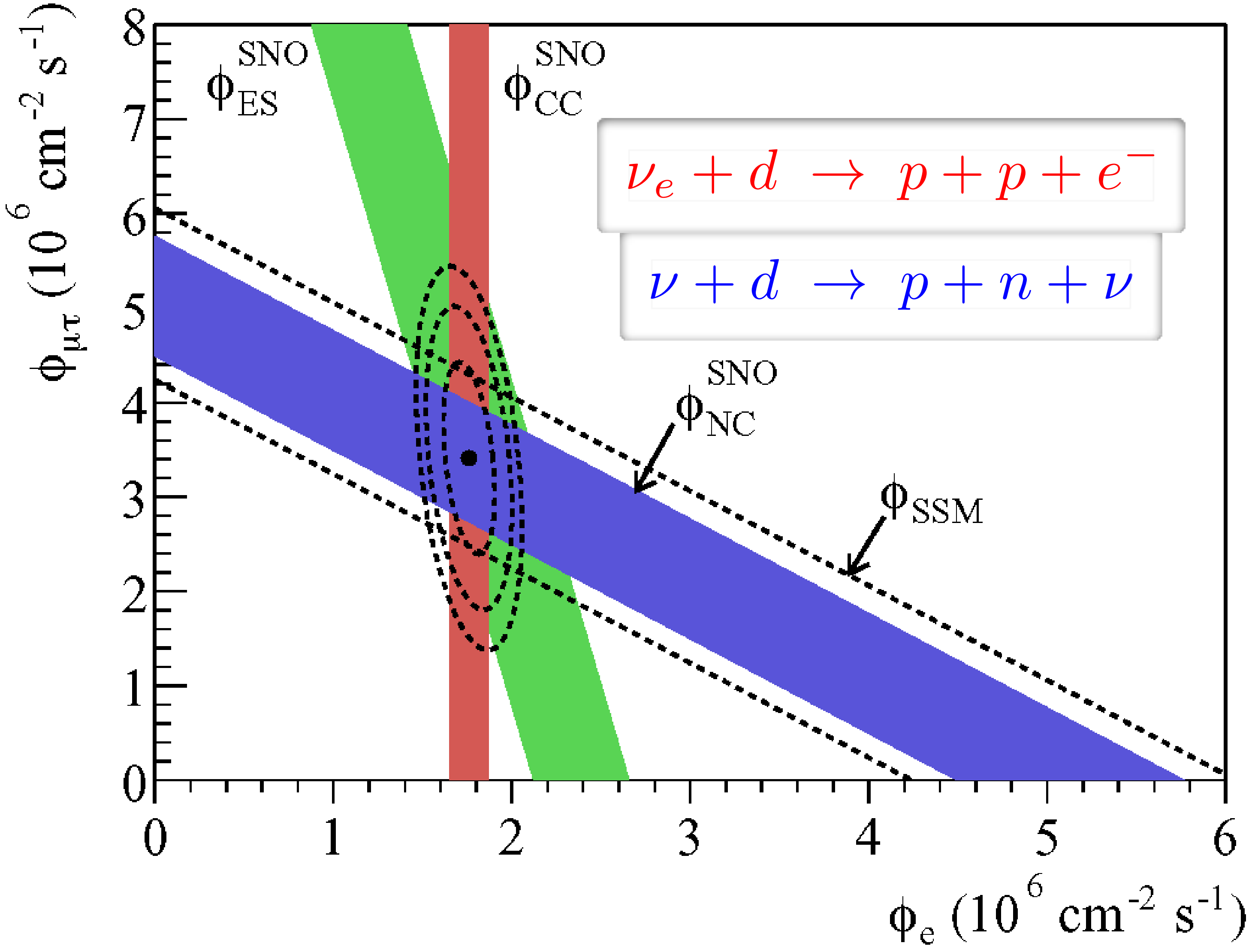
Phys. Rev. Lett. 87, 1562 (1998)



solar neutrinos oscillate!

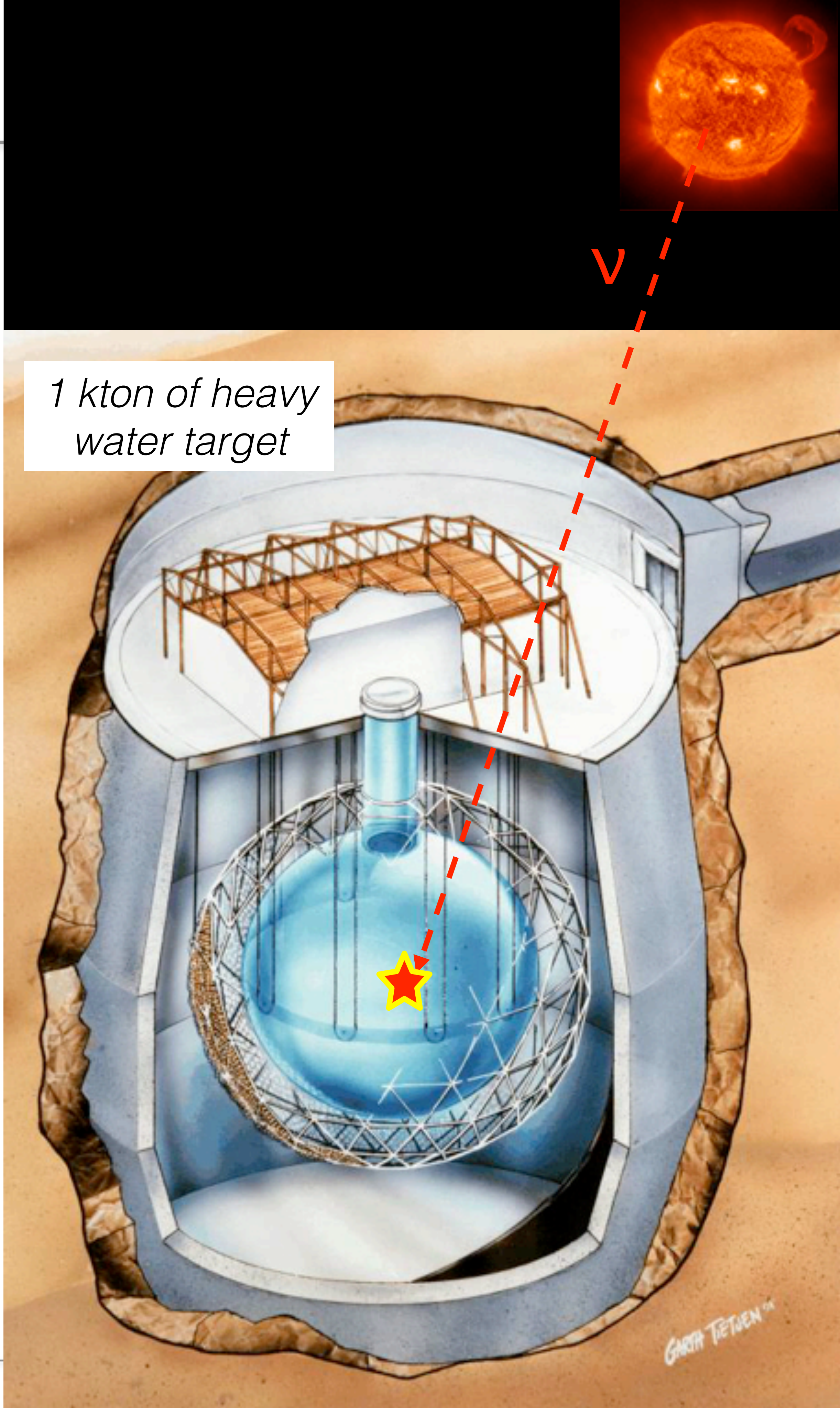
2002:
by exploiting 2 different reactions on deuterium, the SNO experiment proved that ν_e produced in fusion reactions in the sun have turned (oscillated) into $\nu_{\mu,\tau}$ when they are detected on earth

Phys. Rev. Lett. 89, 011301 (2002)



$$\nu_e + d \rightarrow p + p + e^-$$

$$\nu + d \rightarrow p + n + \nu$$



1 kton of heavy water target

ν oscillations imply non-zero ν masses

neutrino oscillations are a quantum mechanical phenomenon

weak (flavor) eigenstates determine how neutrinos are produced and interact

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \neq \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

mass (energy) eigenstates determine how neutrinos propagate in space-time

mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

propagation:

$$\nu_{mj}(t) = e^{-i(E_j t - p_j L)/\hbar} \nu_{mj}$$

production/detection:

$$\left|\nu_j\right\rangle = \sum_{j'} \sum_{l} U_{lj} e^{-i(E_j t - p_j L)} U^*_{j'l} \left|\nu_{j'}\right\rangle$$

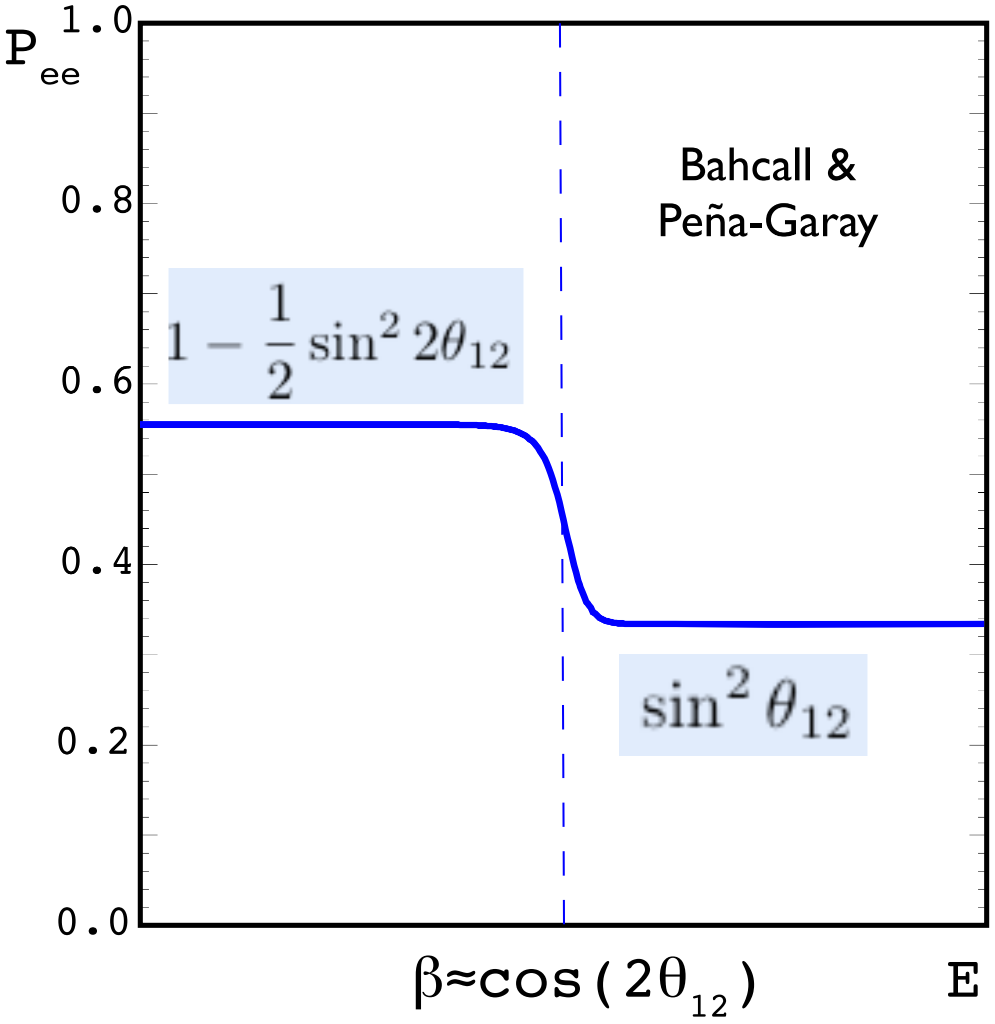
two almost separate 2-flavor ν mixings

neutrino oscillations firmly established

solar, atmospheric, reactor, beam neutrinos give a nice picture of the oscillation of three active flavours

the MSW-LMA solution for solar neutrinos predicts an energy-dependent survival probability for electron neutrinos

$$\delta m^2_{12} \sim 7.5 \times 10^{-5}\mathrm{eV}^2$$
$$\sin^2\theta_{12} \sim 0.3$$
$$\delta m^2_{23} \sim 2.4 \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} \sim 0.4$$
$$\sin^2\theta_{13} \sim 0.02$$

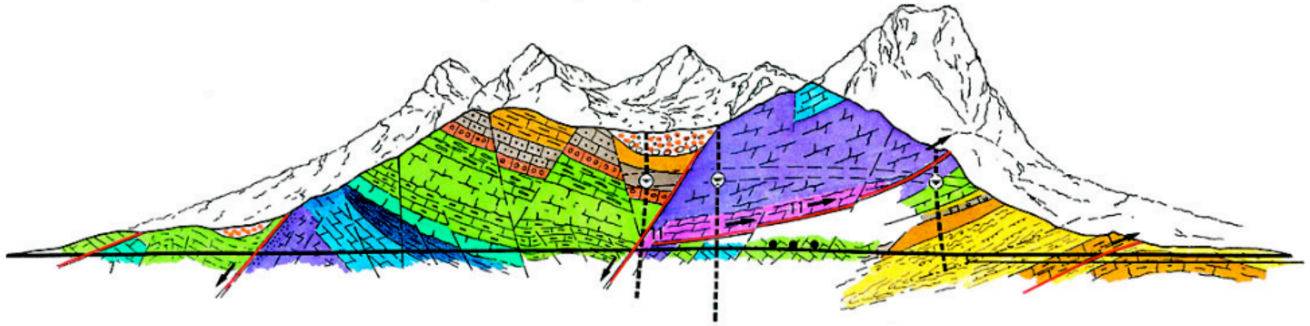


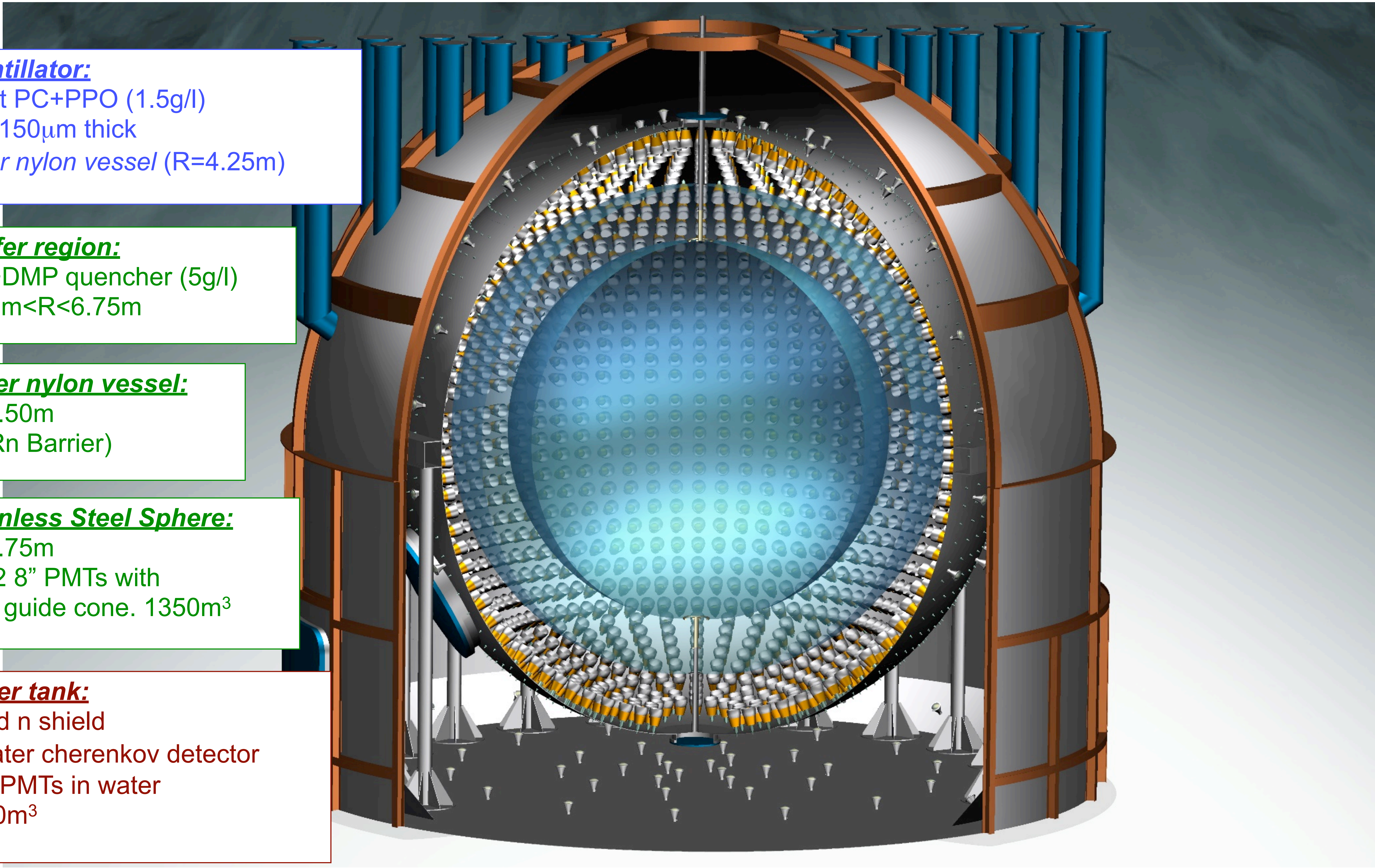
The Borexino project

- Designed to solve the solar neutrino puzzle by finding Be-7 neutrinos
- After SuperK, SNO establish neutrino oscillations:
  - precision neutrino oscillaiton studies
  - precision solar physics

- Has become the standard against which to compare very large, low background experiments

Borexino





Scintillator:
270 t PC+PPO (1.5g/l)
in a 150μm thick
Inner nylon vessel (R=4.25m)

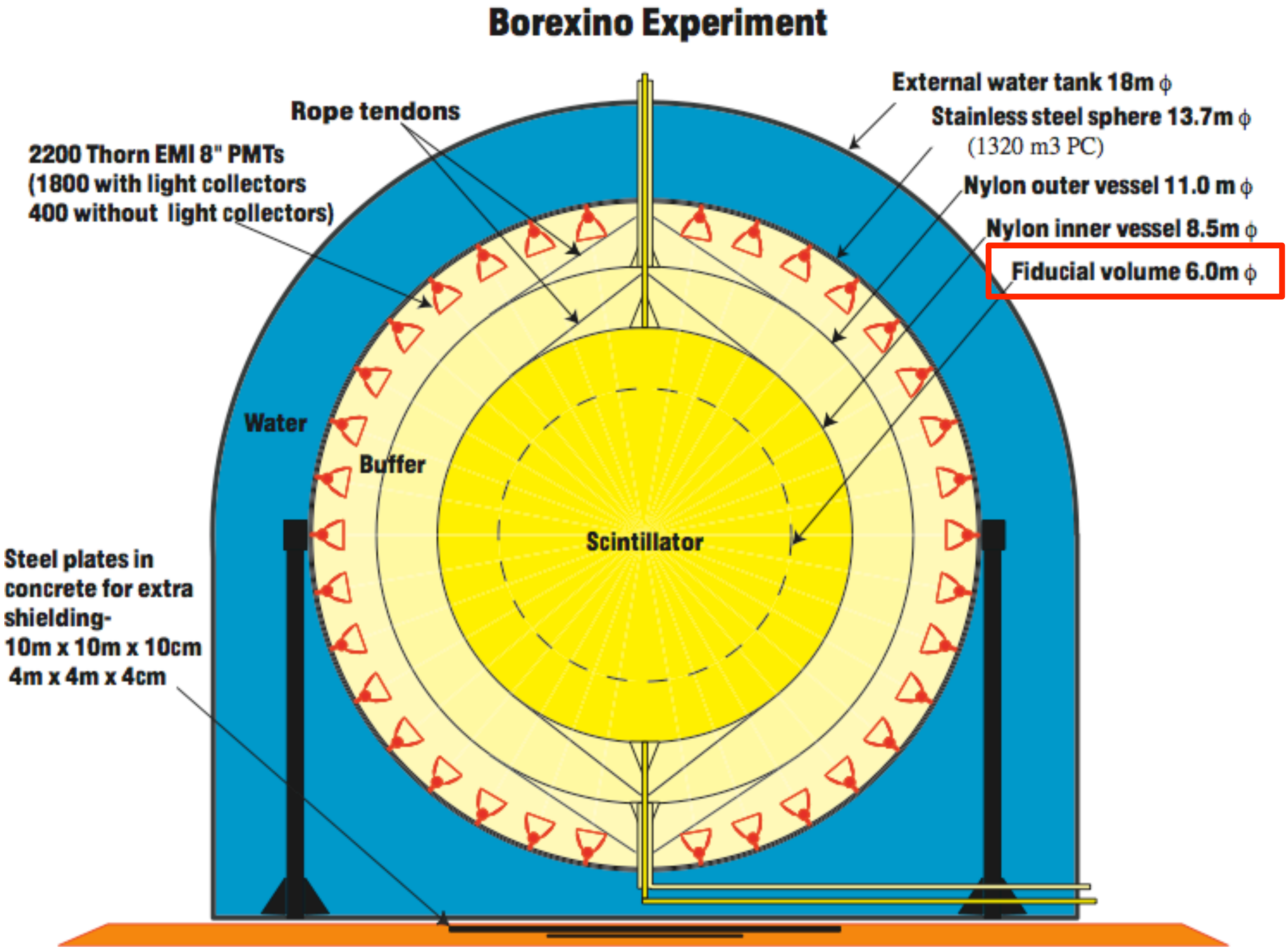
Buffer region:
PC+DMP quencher (5g/l)
4.25m<R<6.75m

Outer nylon vessel:
R=5.50m
(^{222}Rn Barrier)

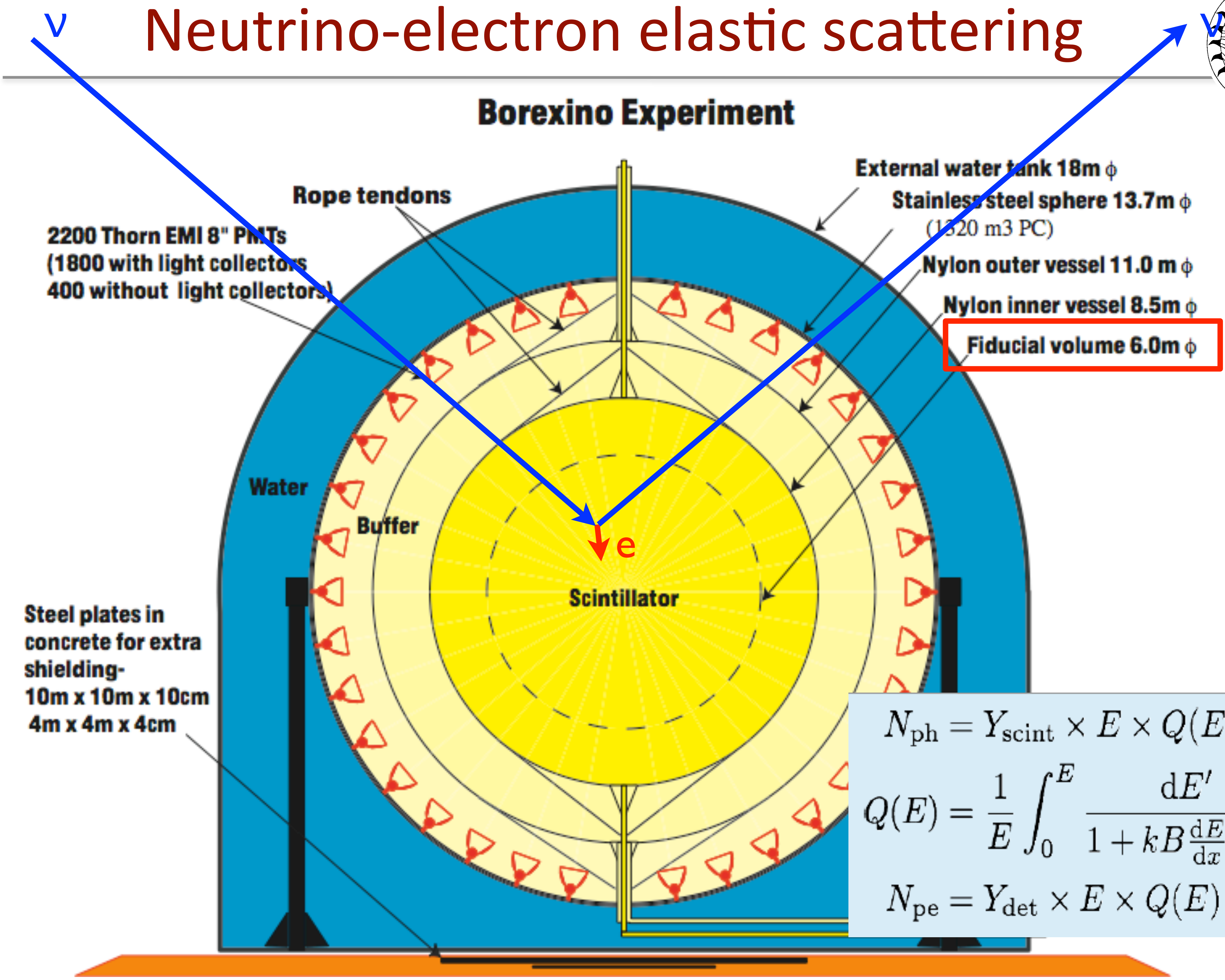
Stainless Steel Sphere:
R=6.75m
2212 8" PMTs with
light guide cone. 1350m^3

Water tank:
γ and n shield
μ water cherenkov detector
208 PMTs in water
2100m^3

Graded shielding design



Neutrino-electron elastic scattering

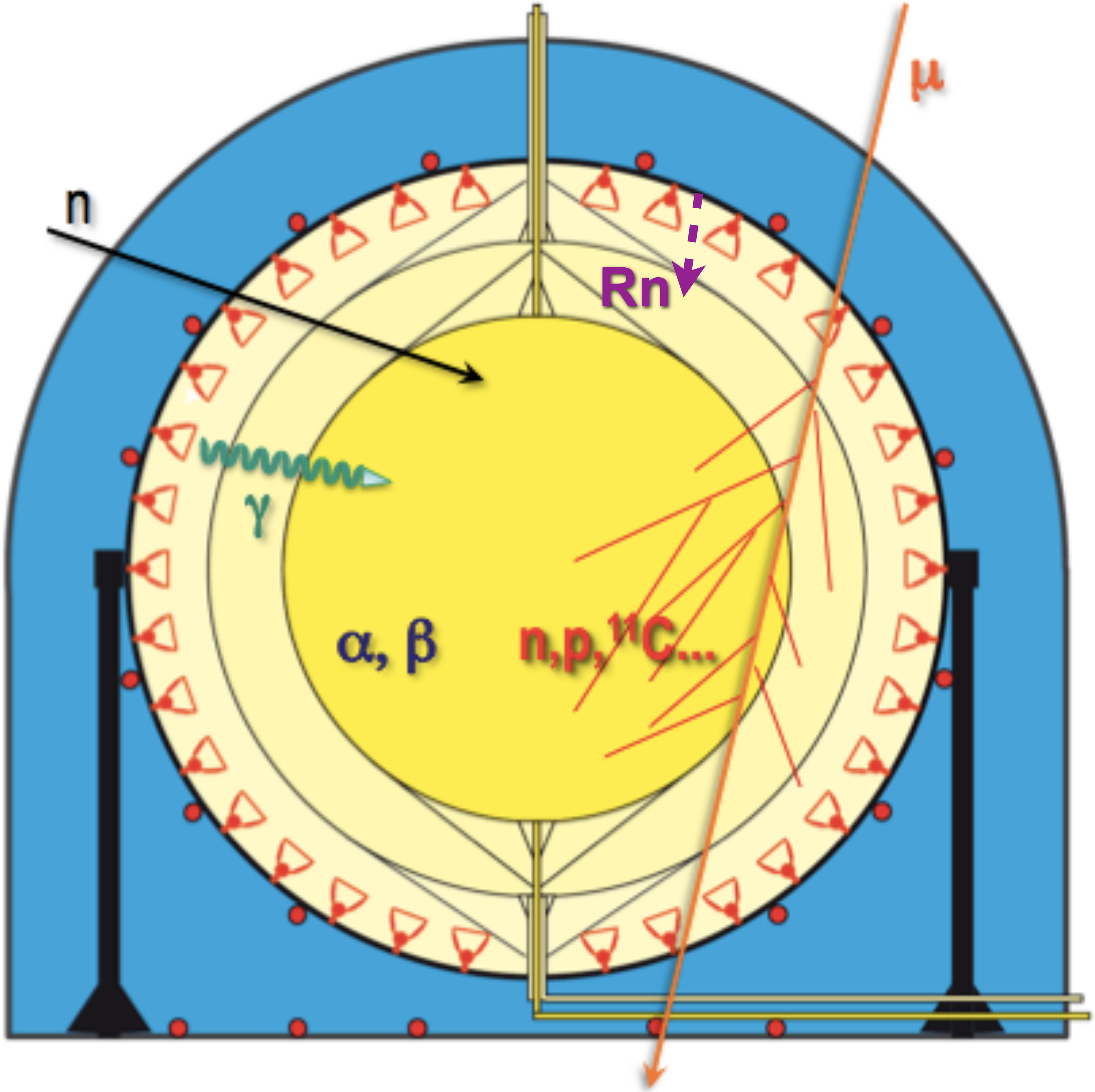


$$N_{\mathrm{ph}} = Y_{\mathrm{scint}} \times E \times Q(E)$$

$$Q(E) = \frac{1}{E} \int_0^E \frac{\mathrm{d}E'}{1 + kB \frac{\mathrm{d}E}{\mathrm{d}x}(E')}$$

$$N_{\mathrm{pe}} = Y_{\mathrm{det}} \times E \times Q(E)$$

extreme radio-purity



internal radioactivity
traces of radioisotopes in the scintillator (U,Th,^{40}K)

external γ rays
from fluid buffer, steel sphere, PMT glass and light concentrators (^{40}K,^{208}Tl,^{214}Bi)

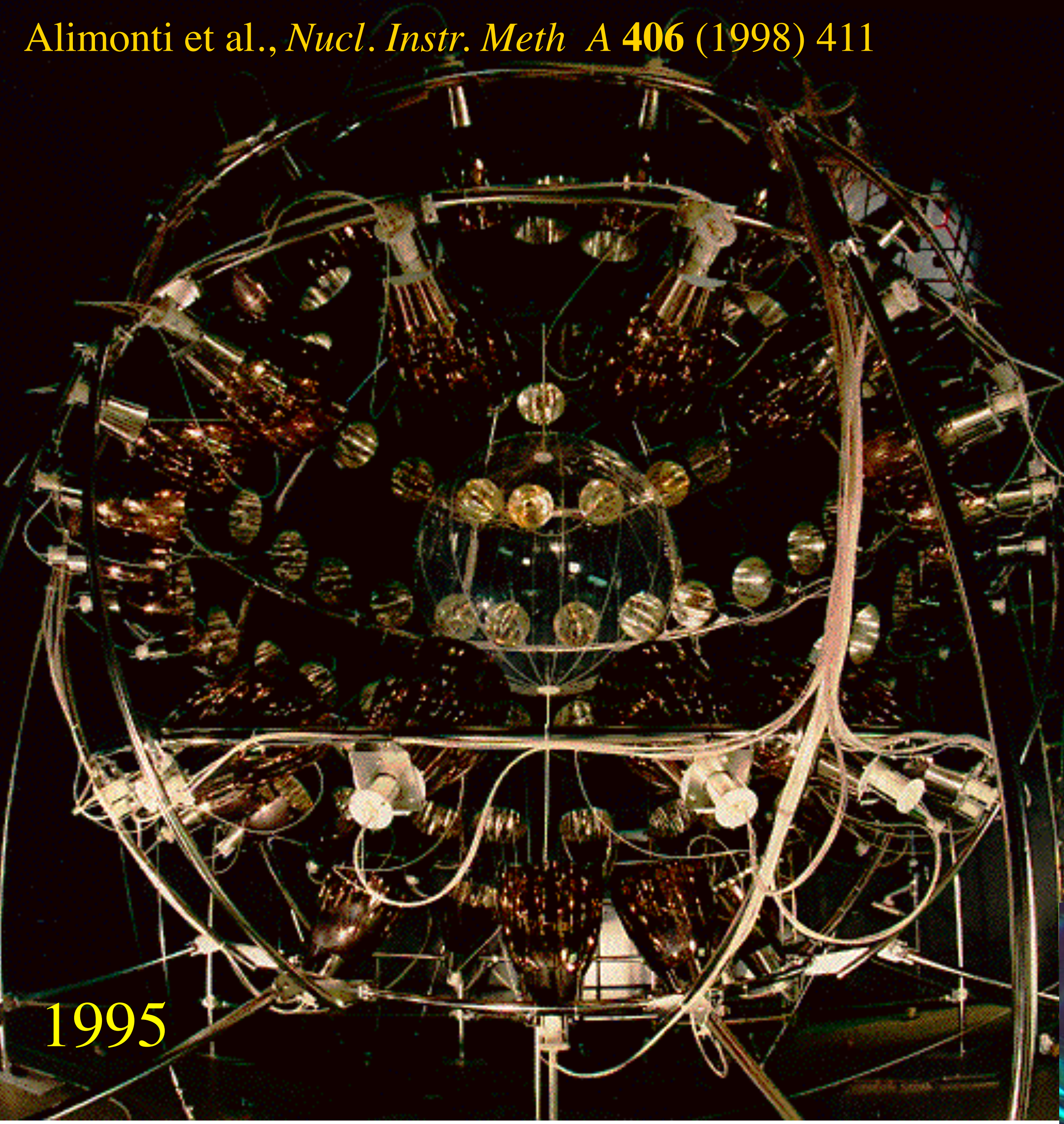
radon emanation
from the PMTs and steel sphere

cosmic muons
and their secondaries

cosmogenics
neutrons and radionuclides from μ spallation and hadronic showers

fast neutrons
from external muons

The Counting Test Facility


Alimonti et al., *Nucl. Instr. Meth A* **406** (1998) 411

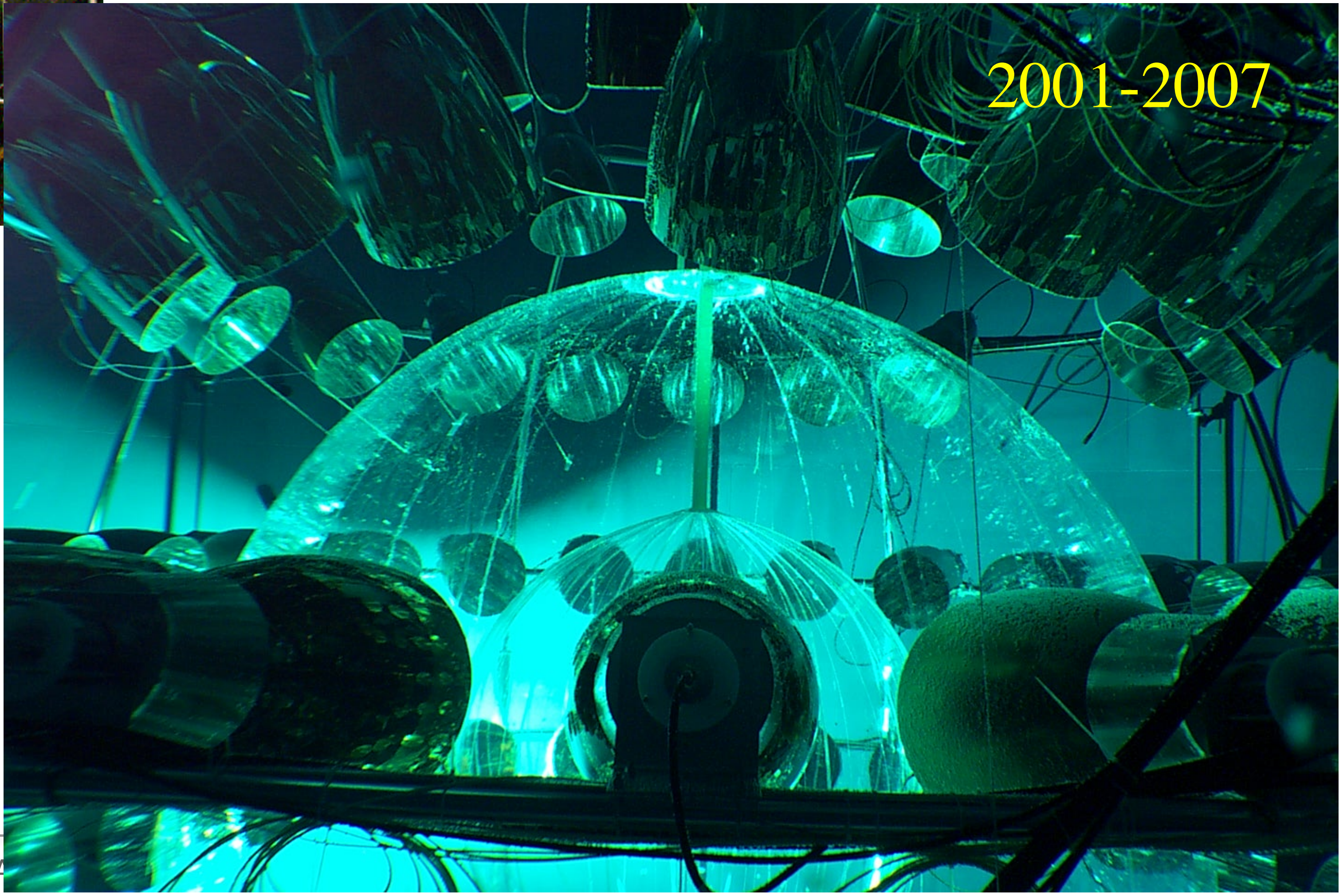
1995

Measurement of scintillator contaminations proving the feasibility of Borexino (1995):

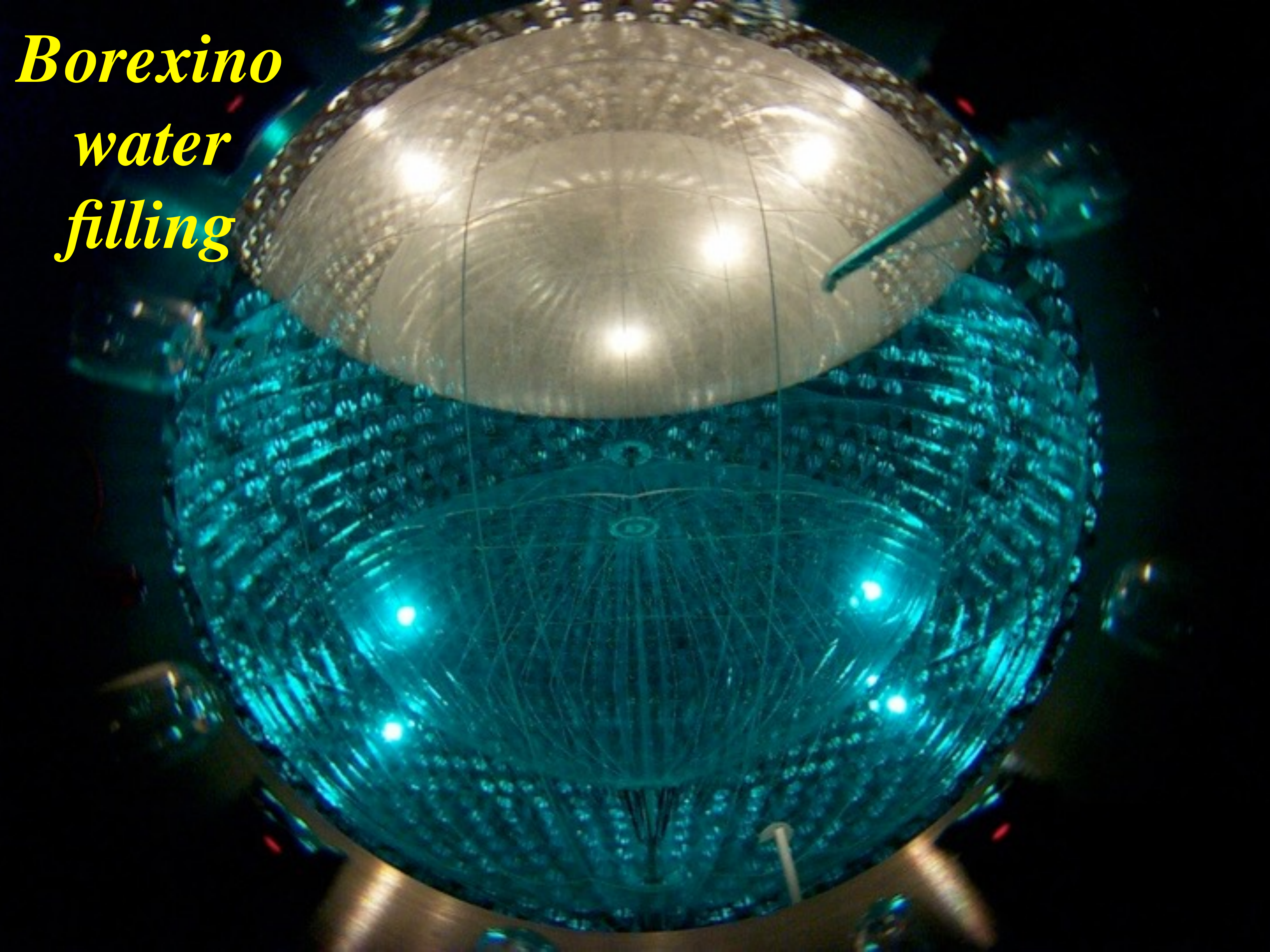
^{238}U = (3.5 ± 1.3) x 10^{-16} g/g
^{232}Th = (4.4 ± 1.5) x 10^{-16} g/g
^{14}C/ ^{12}C = (1.94 ± 0.09) x 10^{-18}

Th and U contamination dominated by external background

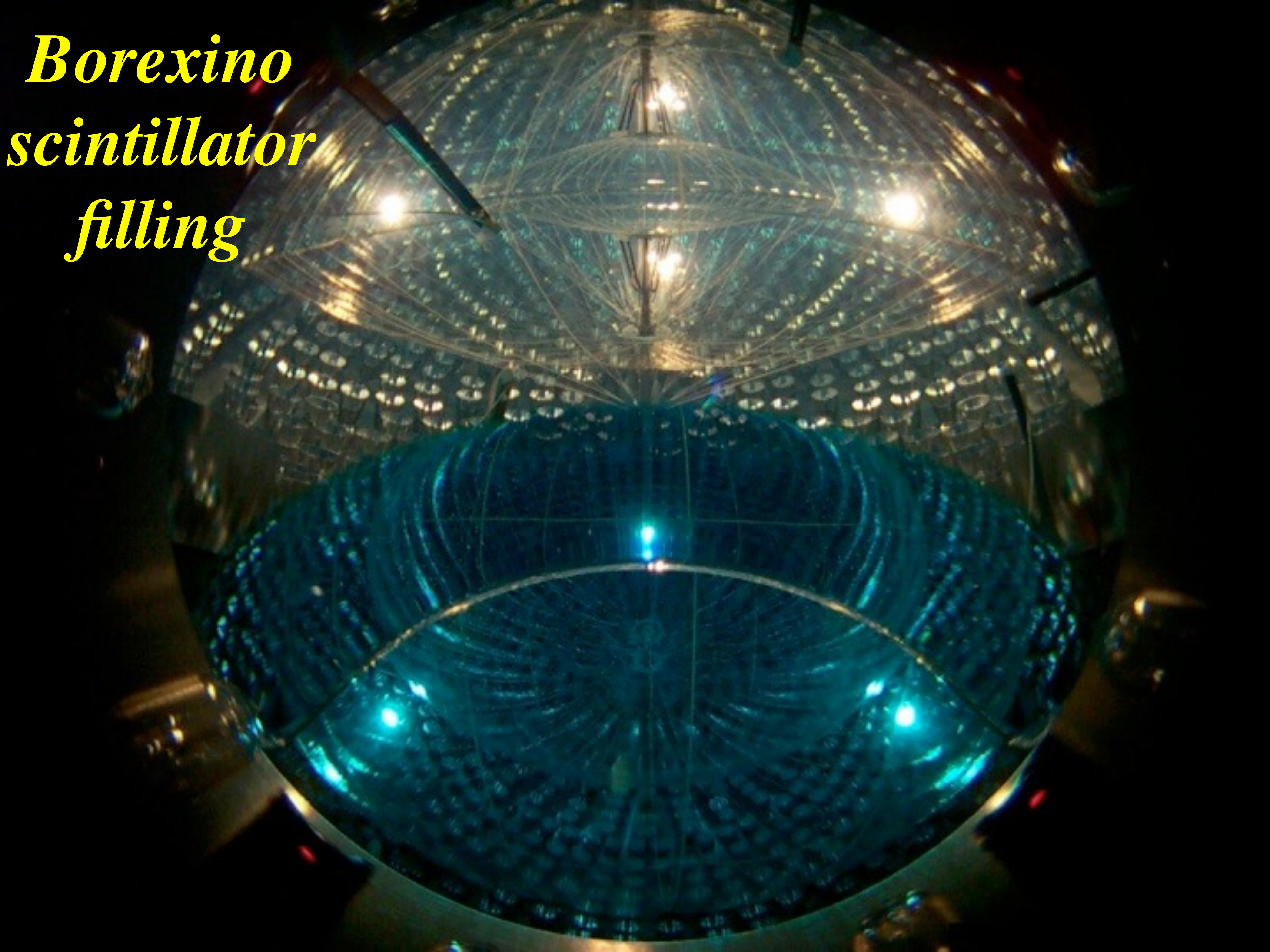
3 campaigns (1995, 2001, 2002-2007):
- testing facility for scintillator (^{14}C)
- materials employed in Borexino (nylon, ropes)
- scintillator purification strategies
- limits on rare phenomena (e-decay, magnetic moment, ...)


2001-2007

Borexino water filling



Borexino scintillator filling



Borexino 2007:

Be-7

B-8

pep

pp

geoneutrinos

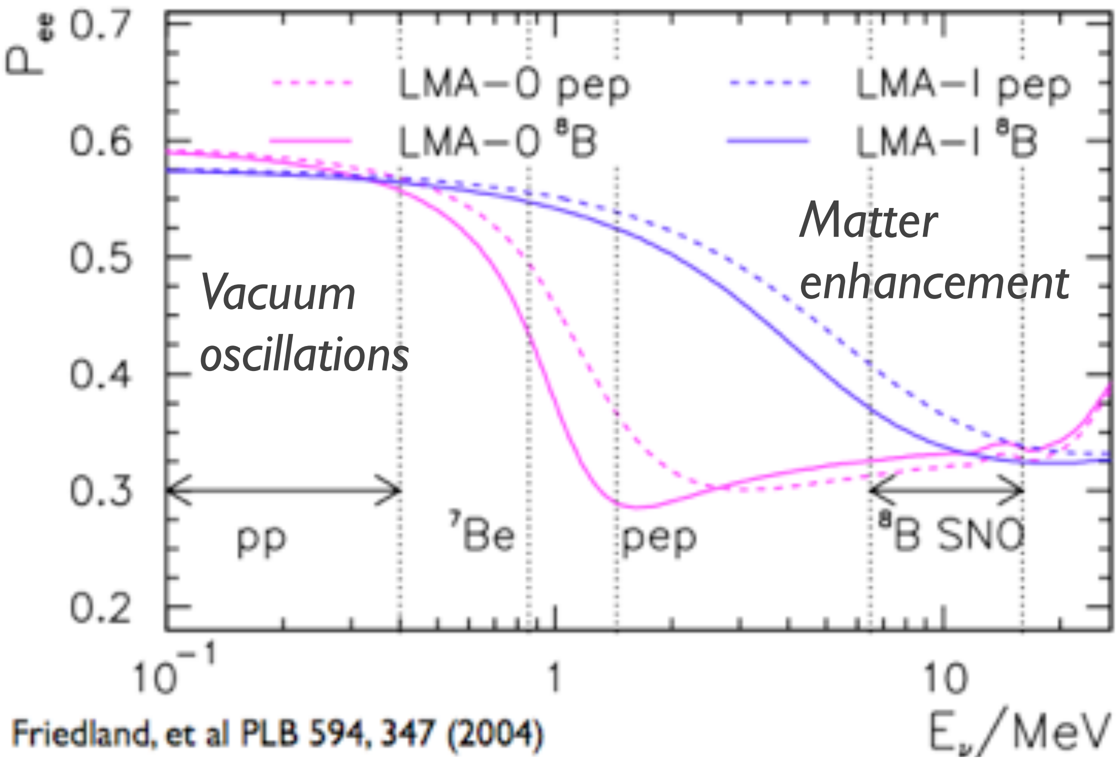
CNO?

supernova ν?

sterile ν?

the full Borexino detector full, May 15 2007

Borexino science



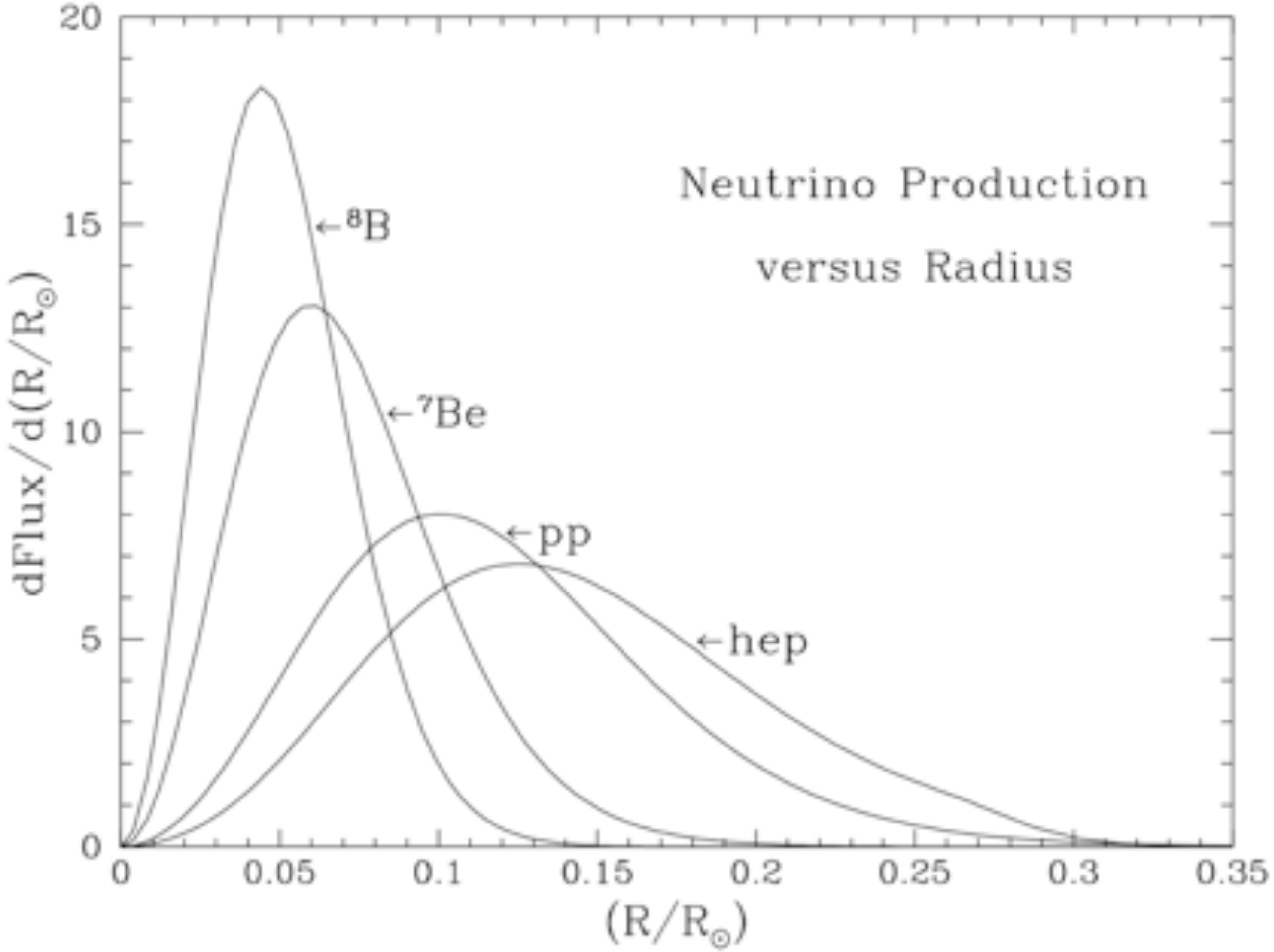
Friedland, et al PLB 594, 347 (2004)

Physics of neutrino oscillations

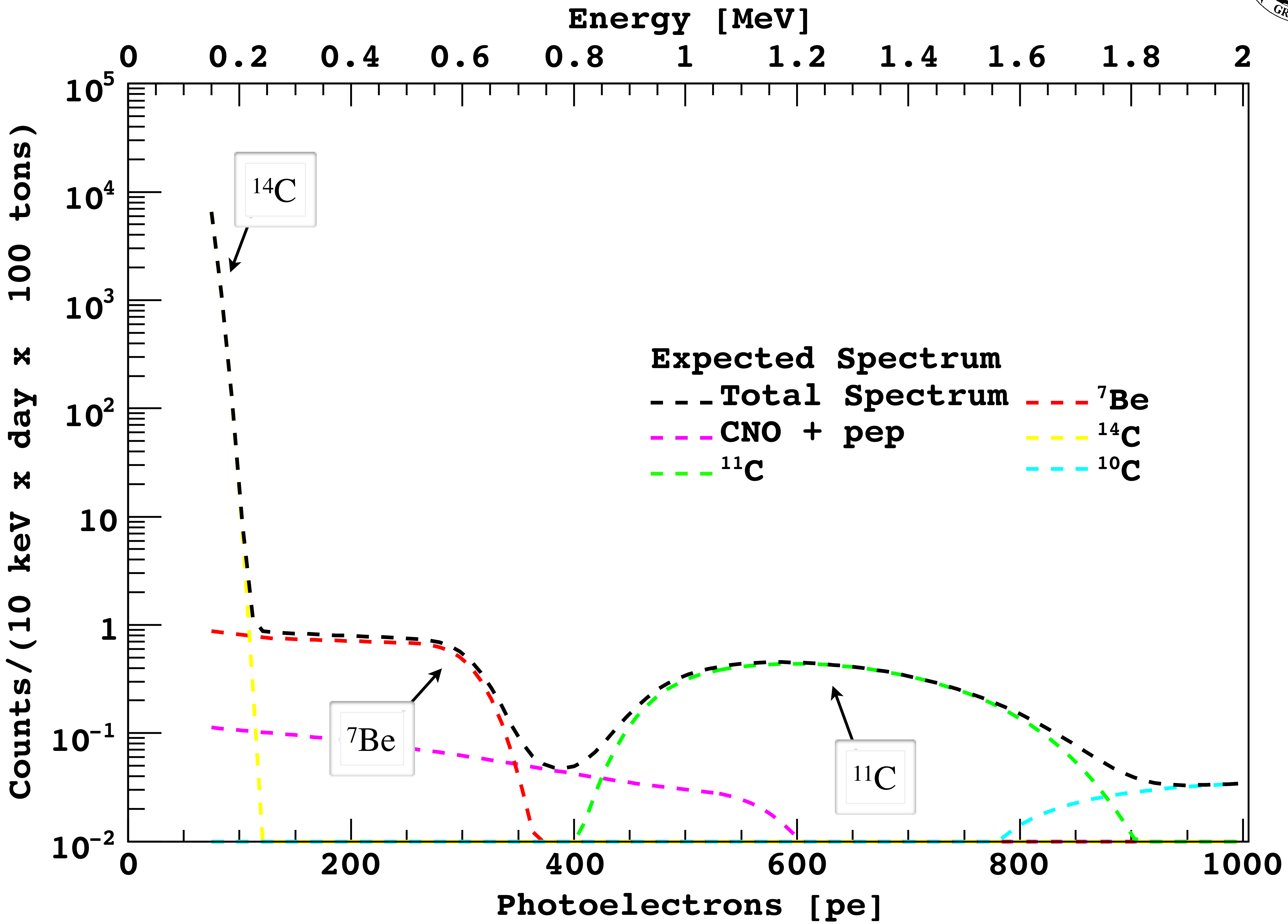
Precision measurements of solar neutrino fluxes can help map out the *transition region,* sensitive to new physics.

Solar physics

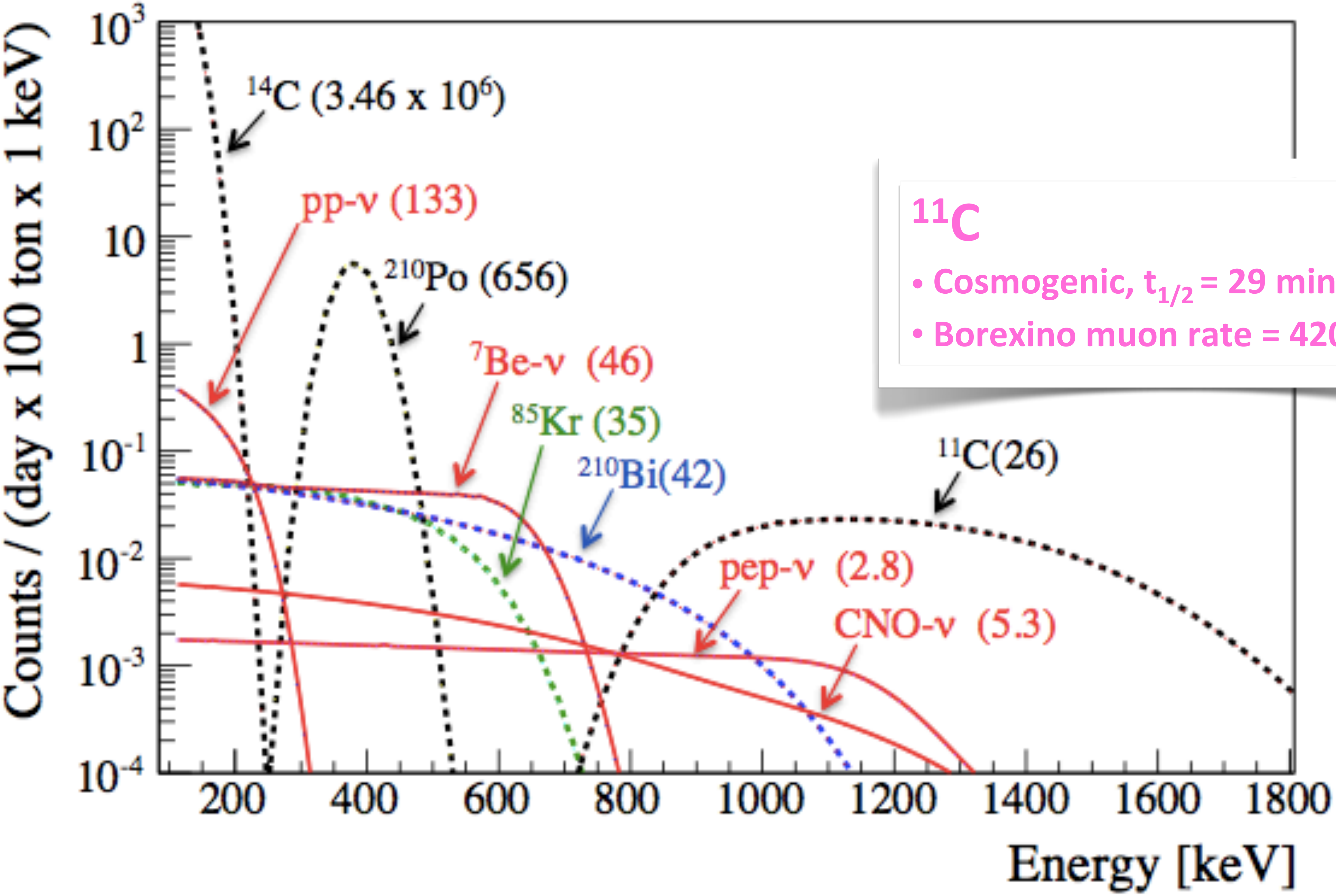
A spectroscopic measurement of the different solar neutrino rates can verify the Standard Solar Model predictions, rule out accretion scenarios and help determine the core C+N abundance.



Expected (dream?) Be-7 neutrino spectrum



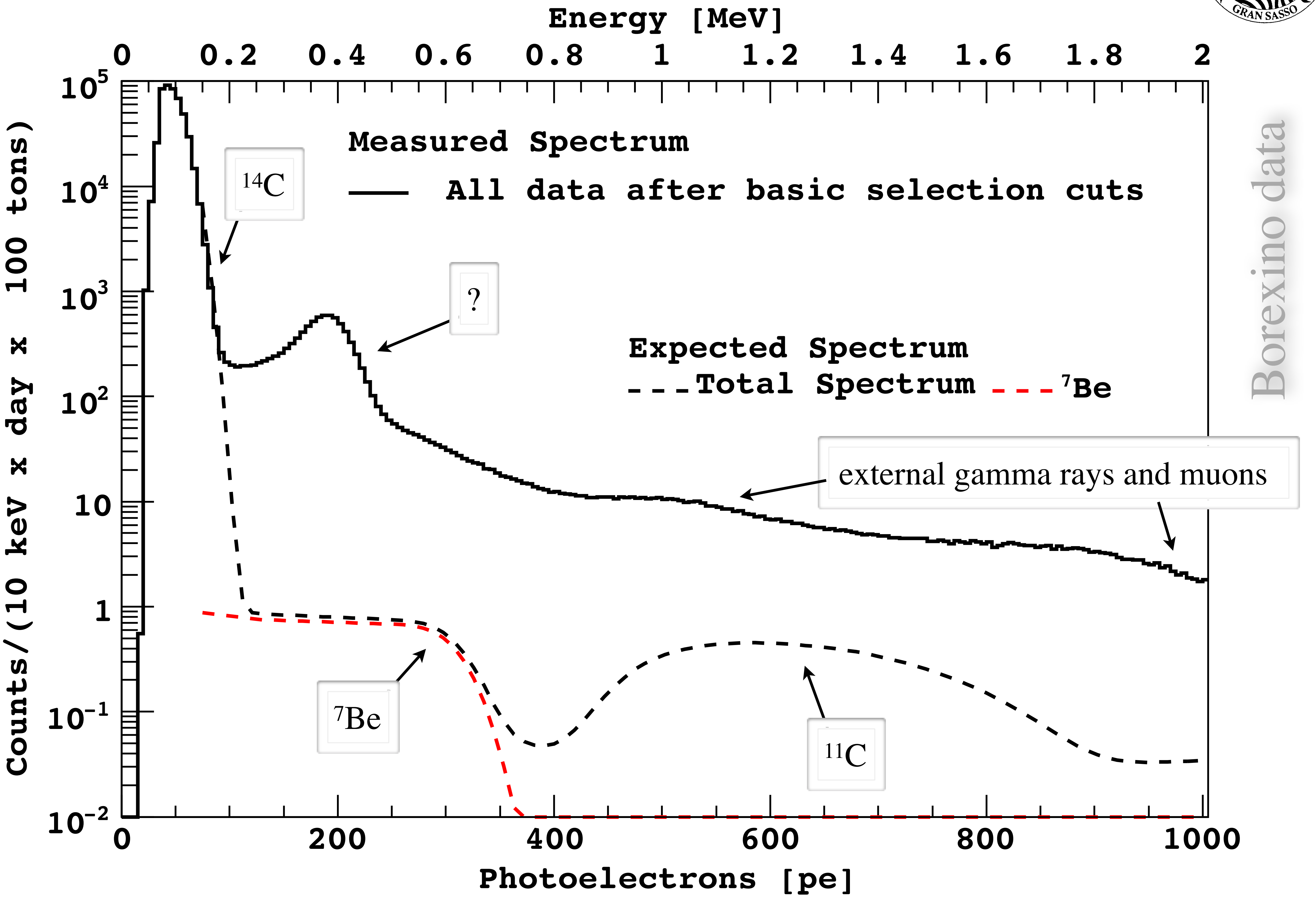
Expected signal and background components



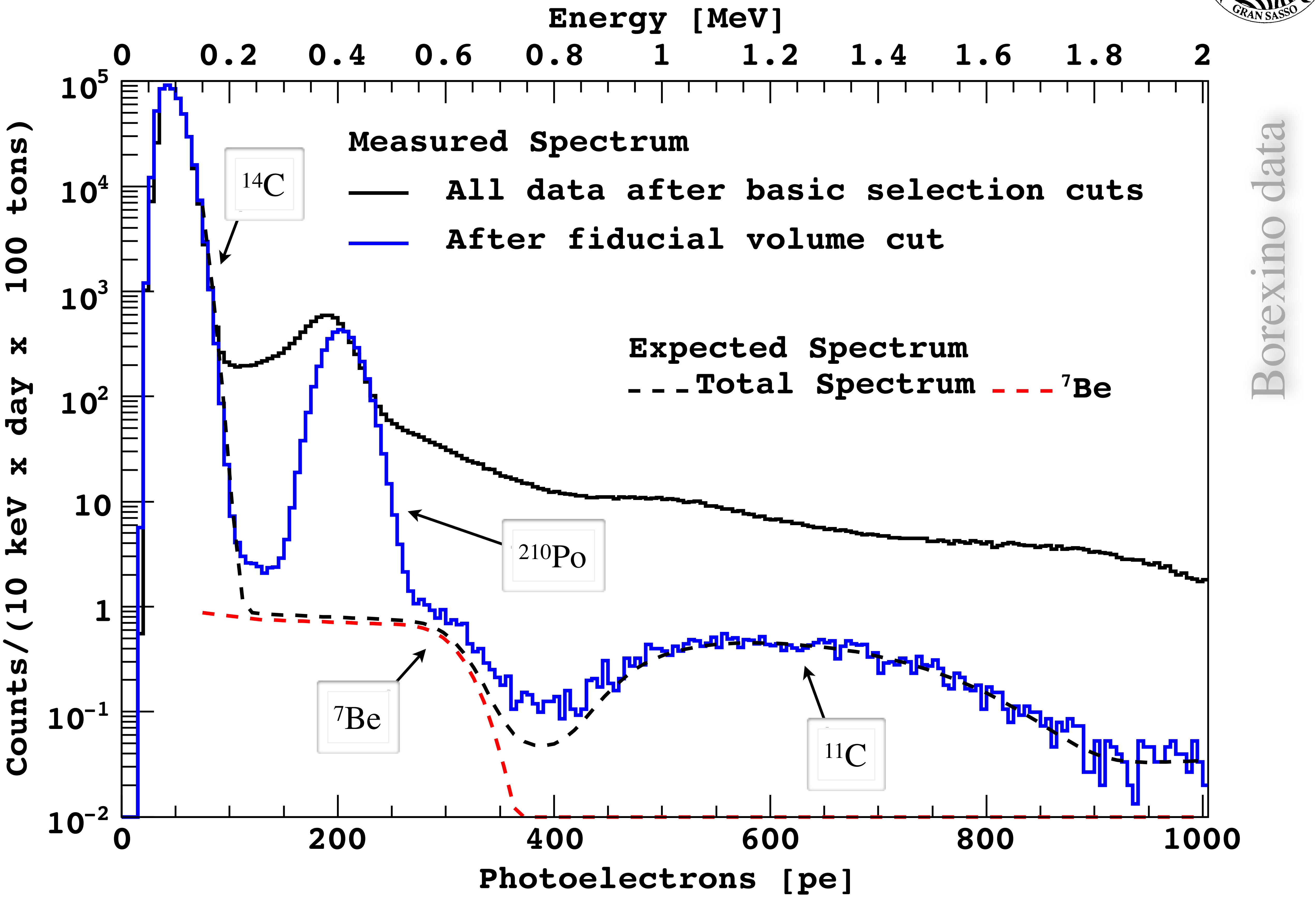
^{11}C

- Cosmogenic, $t_{1/2}$ = 29 min
- Borexino muon rate = 4200/day

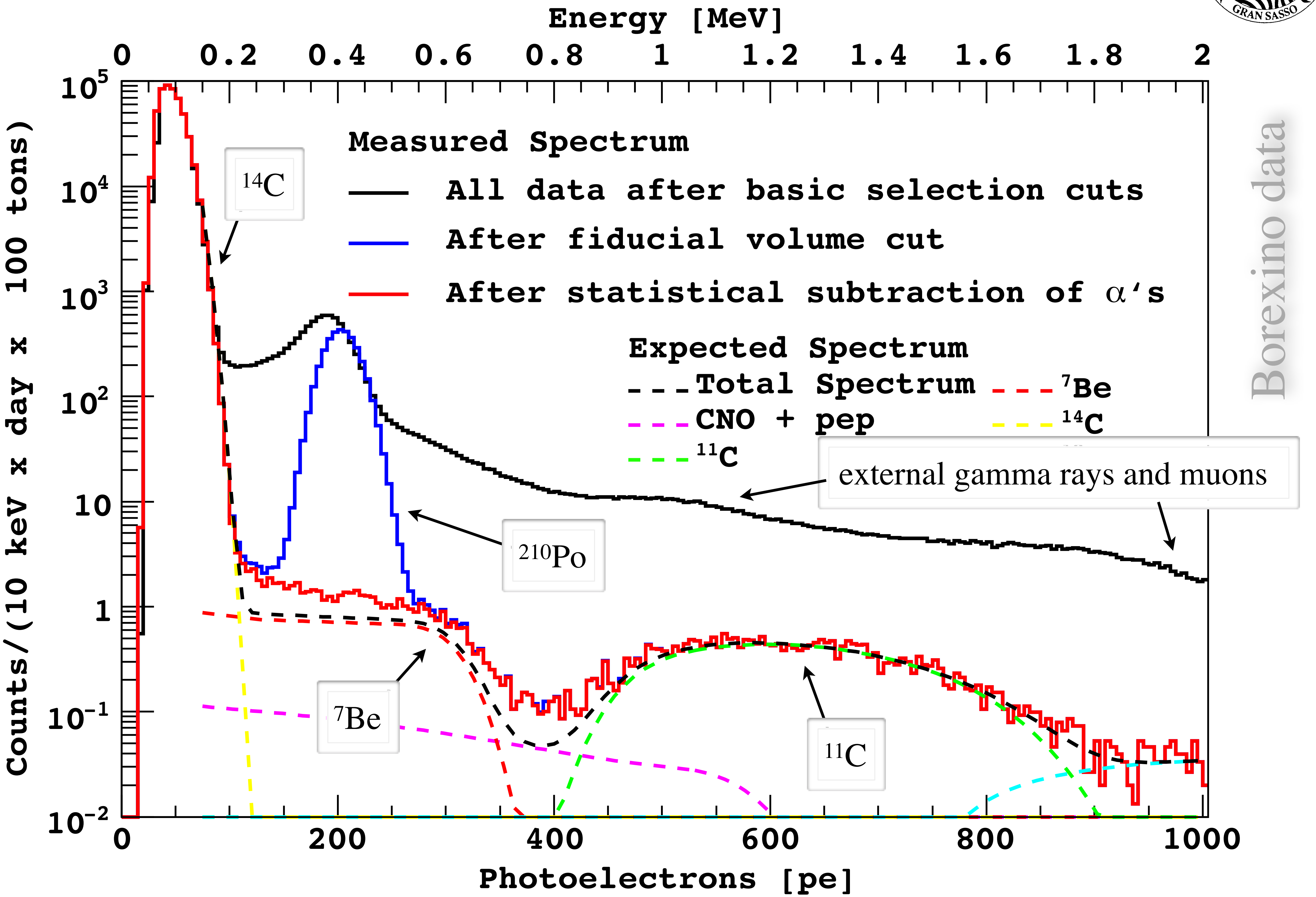
Raw spectrum (no cuts, entire 300 t of scintillator)



Fiducial cut



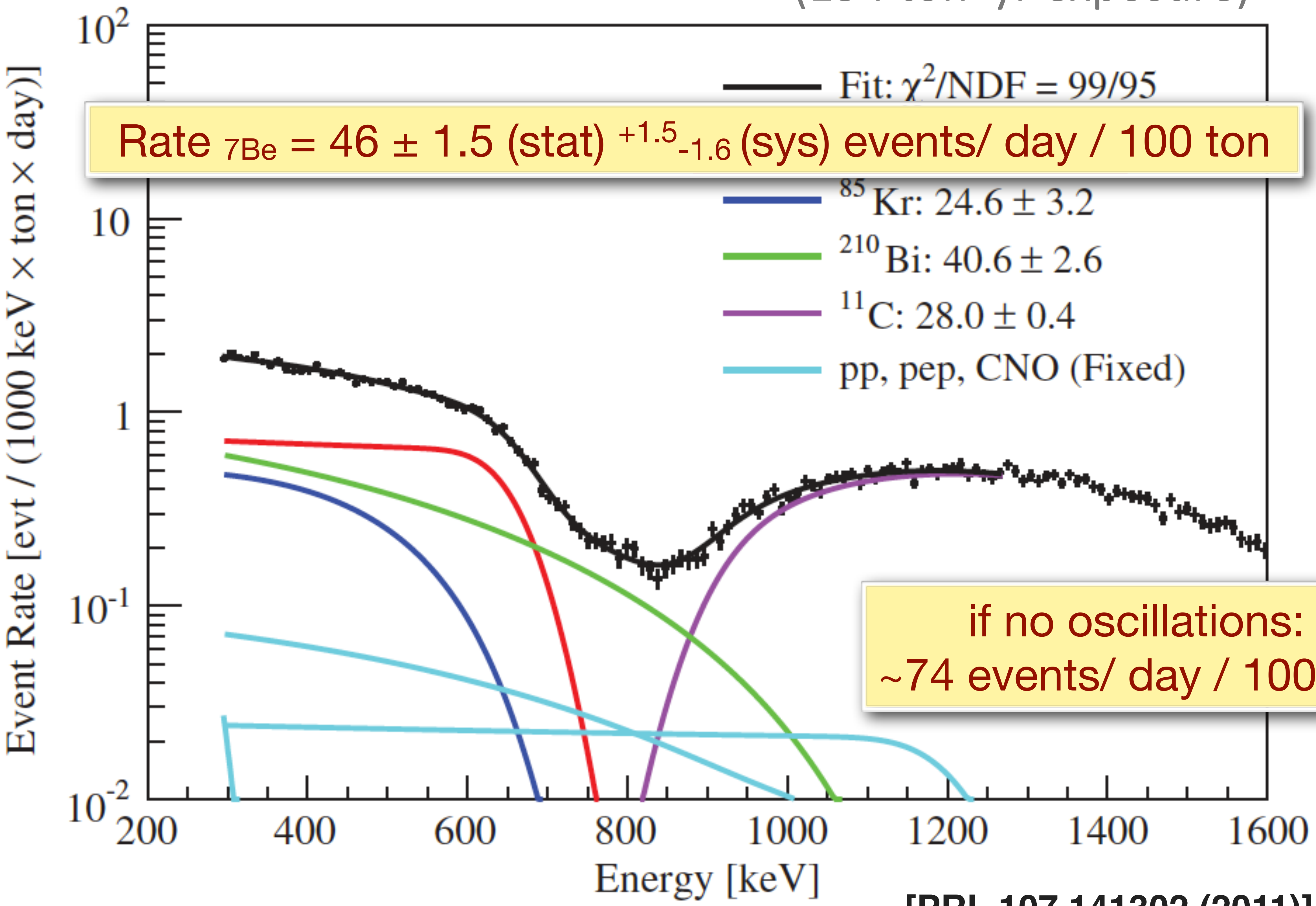
Particle ID



Energy [MeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
Counts/(10 keV x day x 100 tons)
Measured Spectrum
All data after basic selection cuts
After fiducial volume cut
After statistical subtraction of α's
Expected Spectrum
Total Spectrum
^{7}Be
CNO + pep
^{14}C
^{11}C
^{14}C
external gamma rays and muons
^{210}Po
^{7}Be
^{11}C
Borexino data
0
200
400
600
800
1000
Photoelectrons [pe]

Be-7 precision measurement (2007-2010)

(154 ton·yr exposure)



Rate $_{7Be}$ = 46 ± 1.5 (stat) $^{+1.5}_{-1.6}$ (sys) events/ day / 100 ton

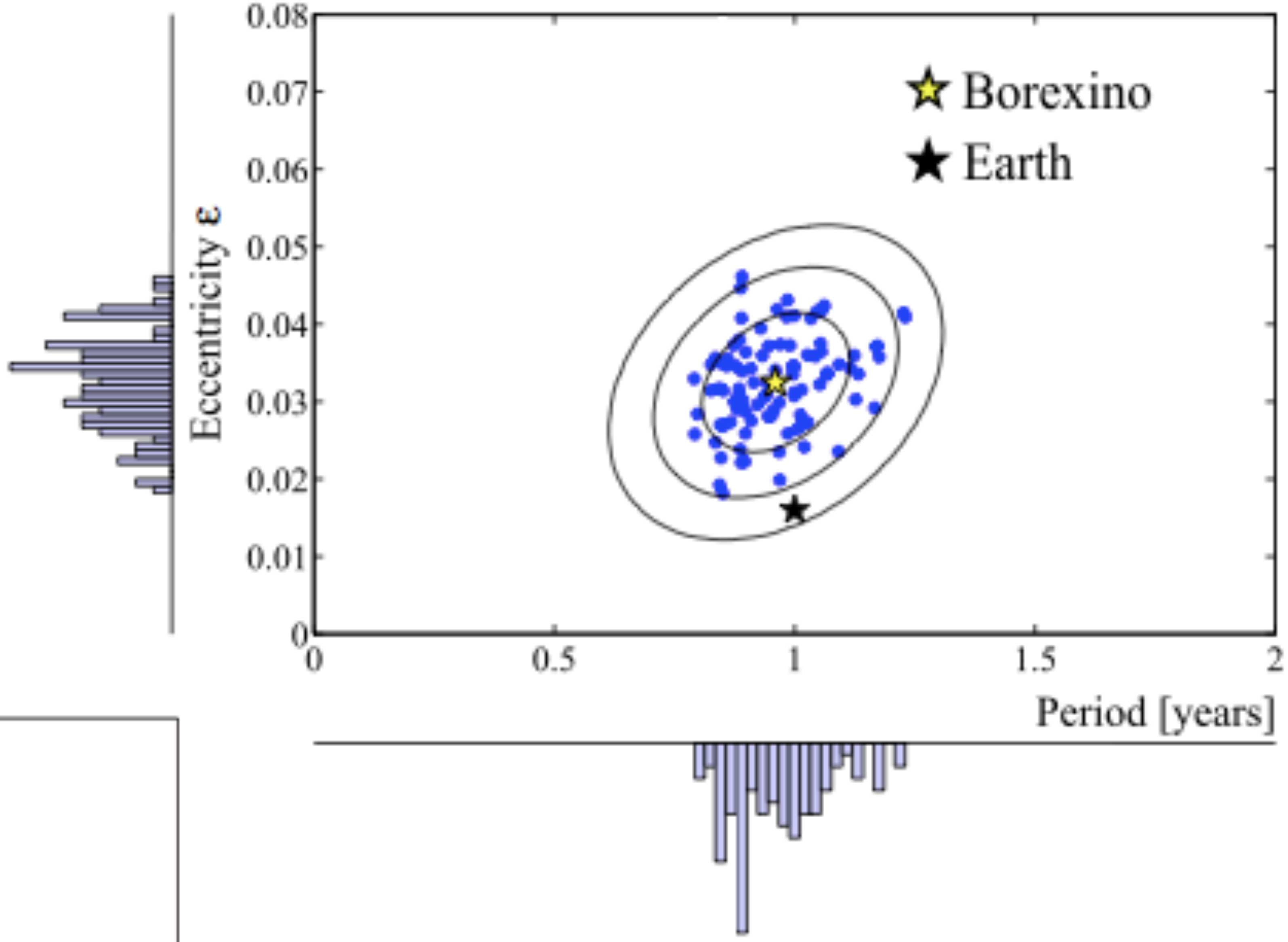
if no oscillations:
~74 events/ day / 100 ton

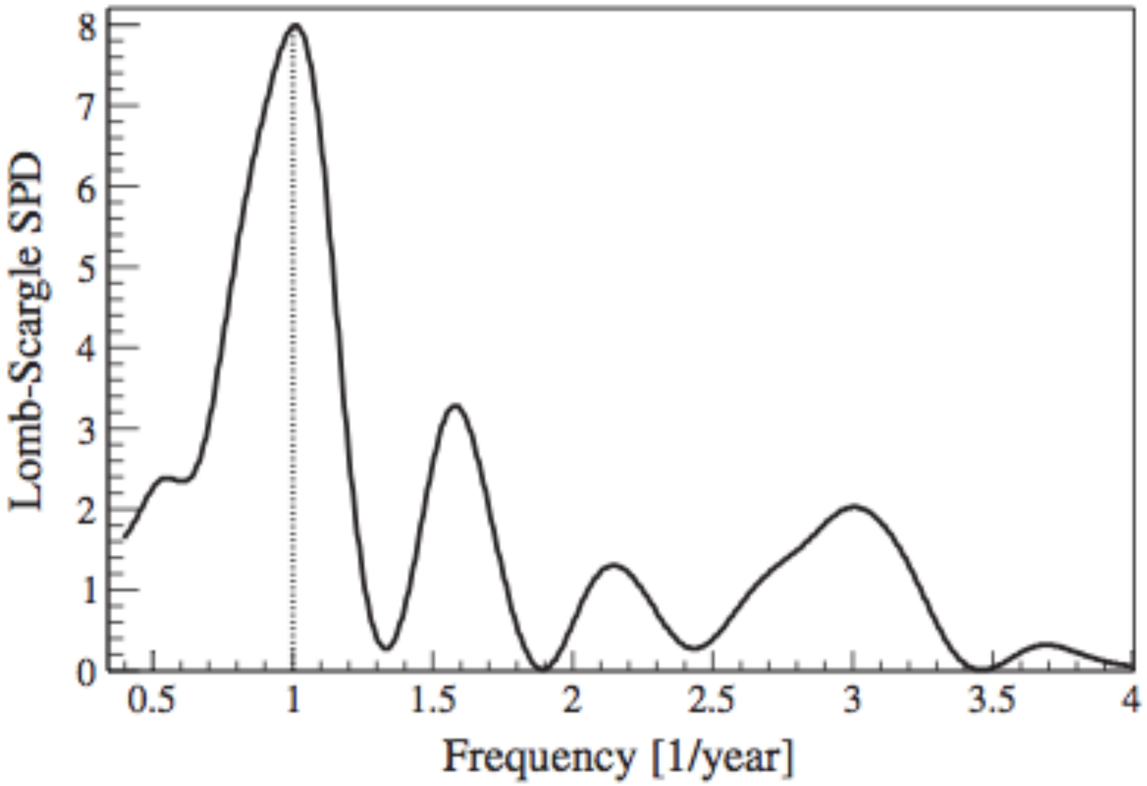
[PRL 107 141302 (2011)]

Seasonal variation of Be-7 flux

empirical mode decomposition

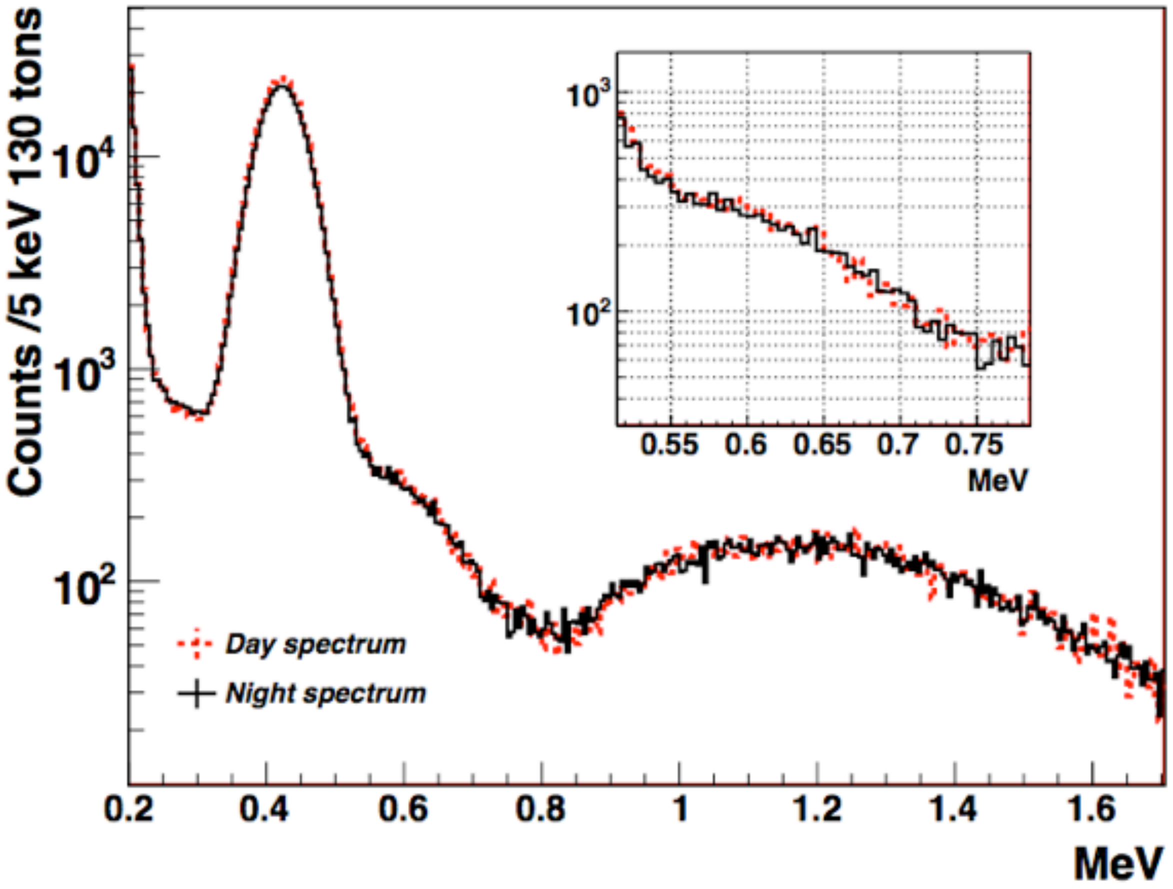
(intrinsic mode functions)





PRD 89, 112007 (2014)

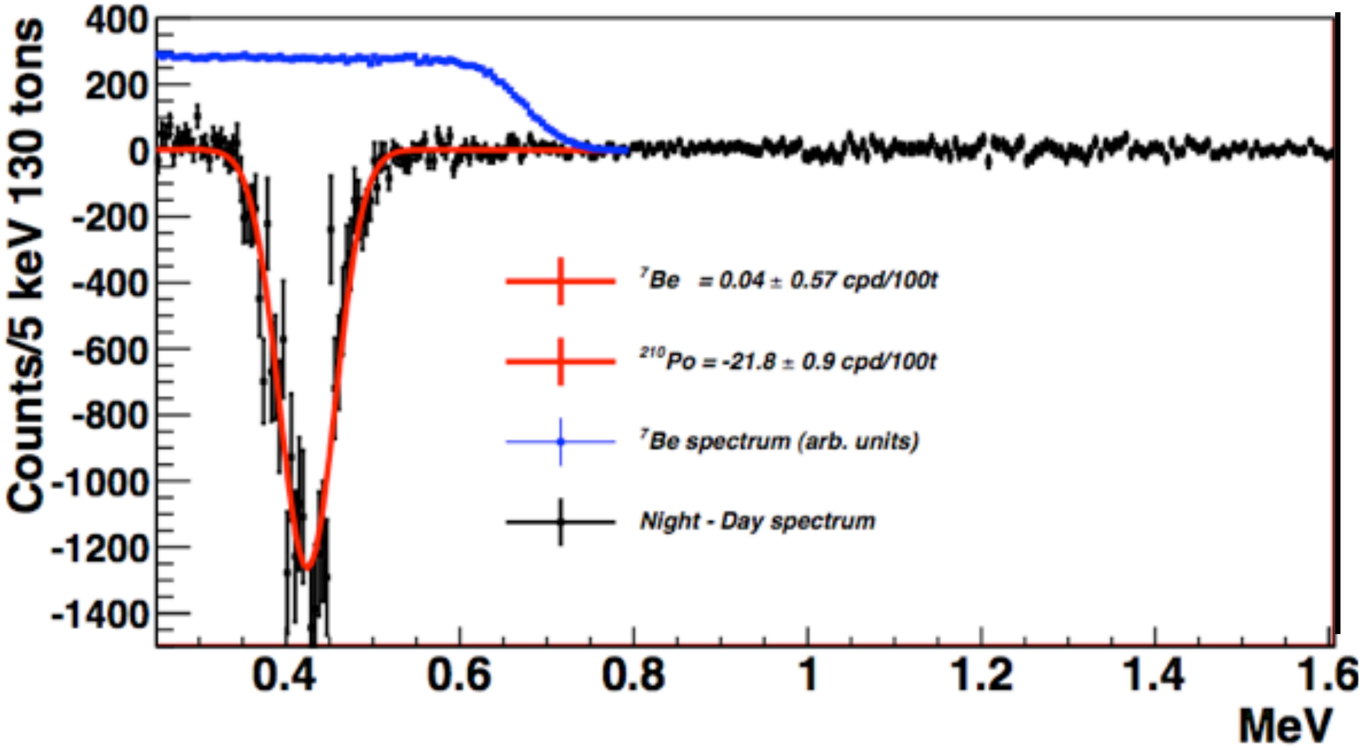
no day/night effect



matter effects of neutrinos crossing the earth could enhance the night rate by regeneration of electron neutrinos

$$A_{dn} = 2\,\frac{R_N - R_D}{R_N + R_D}$$

depends on:
oscillation parameters and neutrino energy



Source	A_{dn} error
Live-time	< 5 x 10^{-4}
Cut efficiency	0.001
^{210}Bi time variation	± 0.005
Fit procedure	± 0.005
Sys error	0.007

$$A_{dn} = 0.001 \pm 0.012\ (stat) \pm 0.007\ (syst)$$

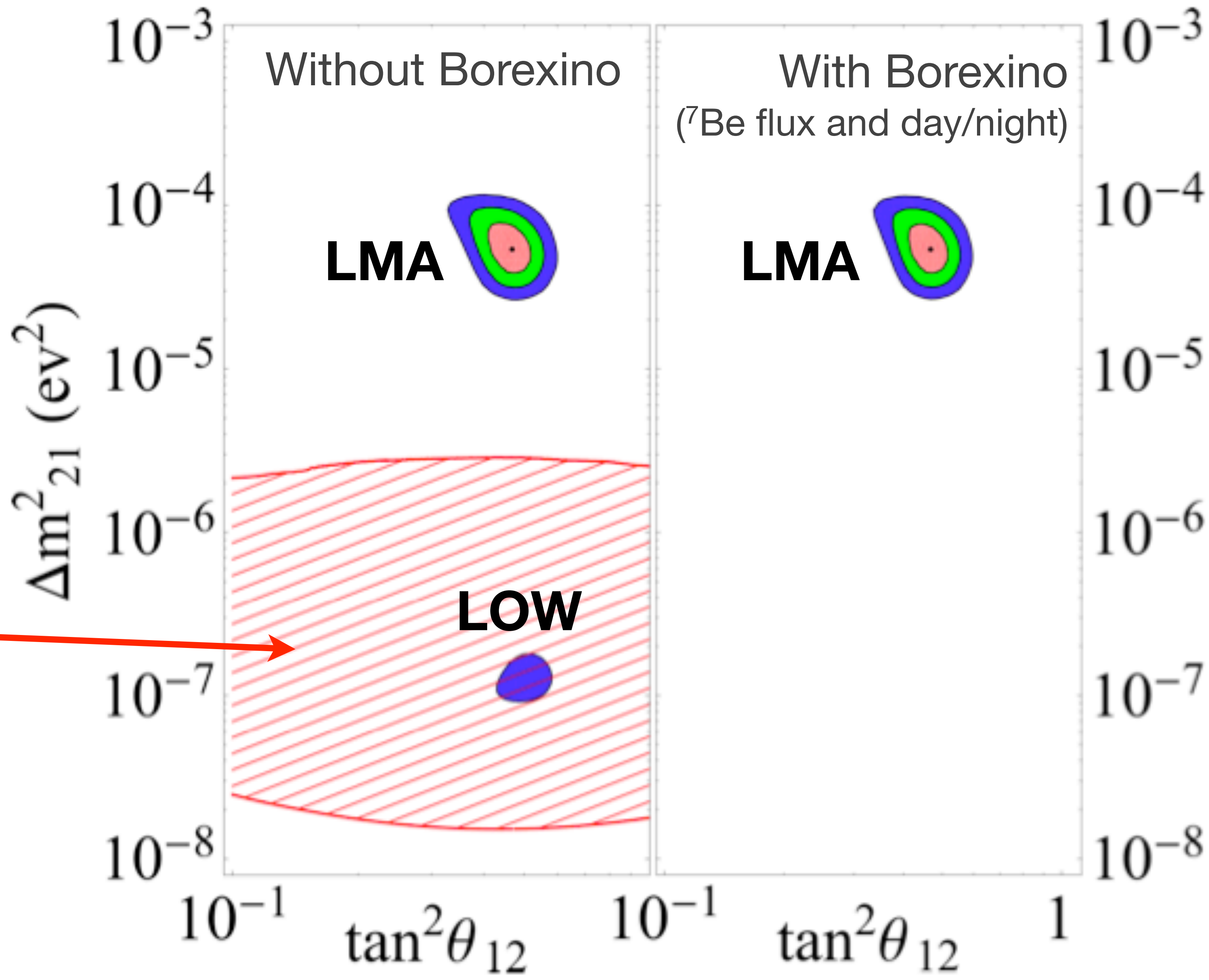
[PLB 707 (2012) 22]

effect on neutrino oscillations

MSW	A_{dn}
LMA	~ 0%
LOW	23 ± 11%

Best fit:
$\Delta m^2 = 5.3 \times 10^{-5}$ eV^2
$\tan^2\theta = 0.46$

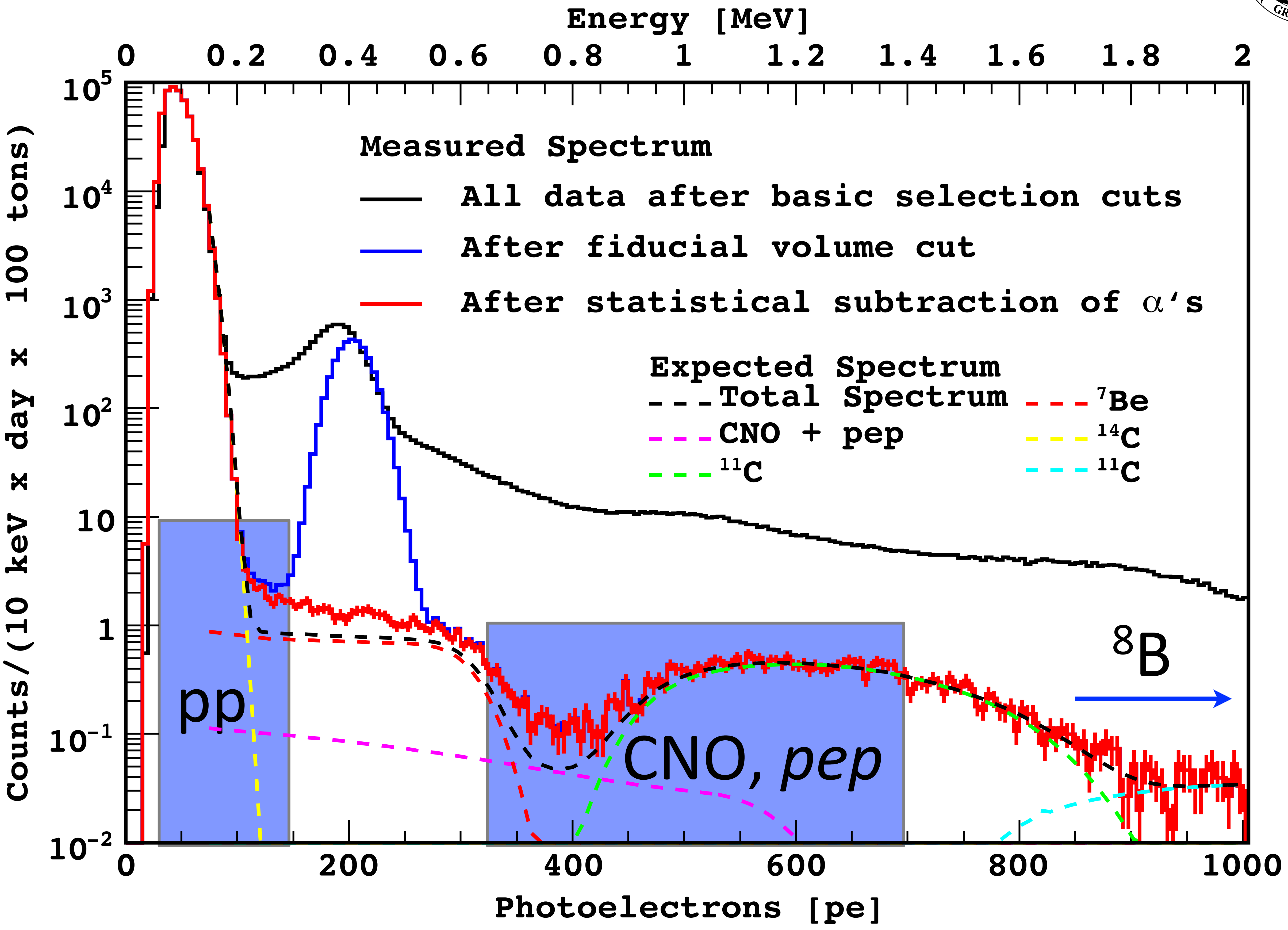
Excluded by Day/Night 99.73% CL



LOW is excluded at > 8.5 σ

[PLB 707 (2012) 22]

Beyond Be-7 neutrinos



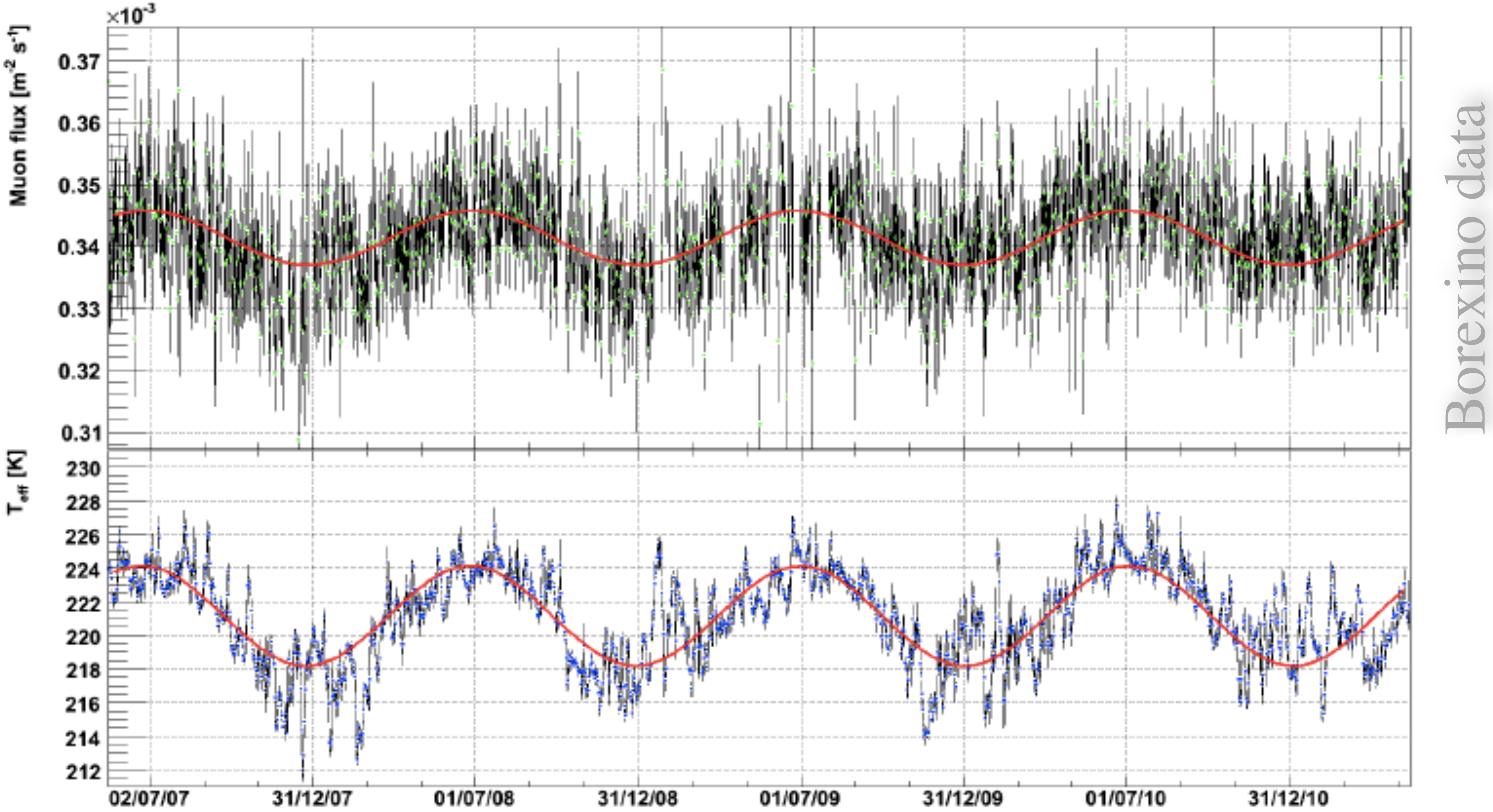
pep and CNO solar neutrinos

- Tests of MSW-LMA with ^{7}Be limited due to uncertainty in solar flux.
- *pep* flux predicted with higher precision, 1.2% uncertainty. Allows for more stringent tests of oscillation models. Also mono-energetic.
- CNO fluxes directly related to Solar Metallicity. It could allow to discern between High Z and Low Z models.
- Tests of MSW-LMA at intermediate energy (vacuum <-> matter)
- Small fluxes: ~5 interactions per day per 100 tons of target. End points 1-2 MeV.
- ^{11}C is the dominant background in Borexino (muon-related)

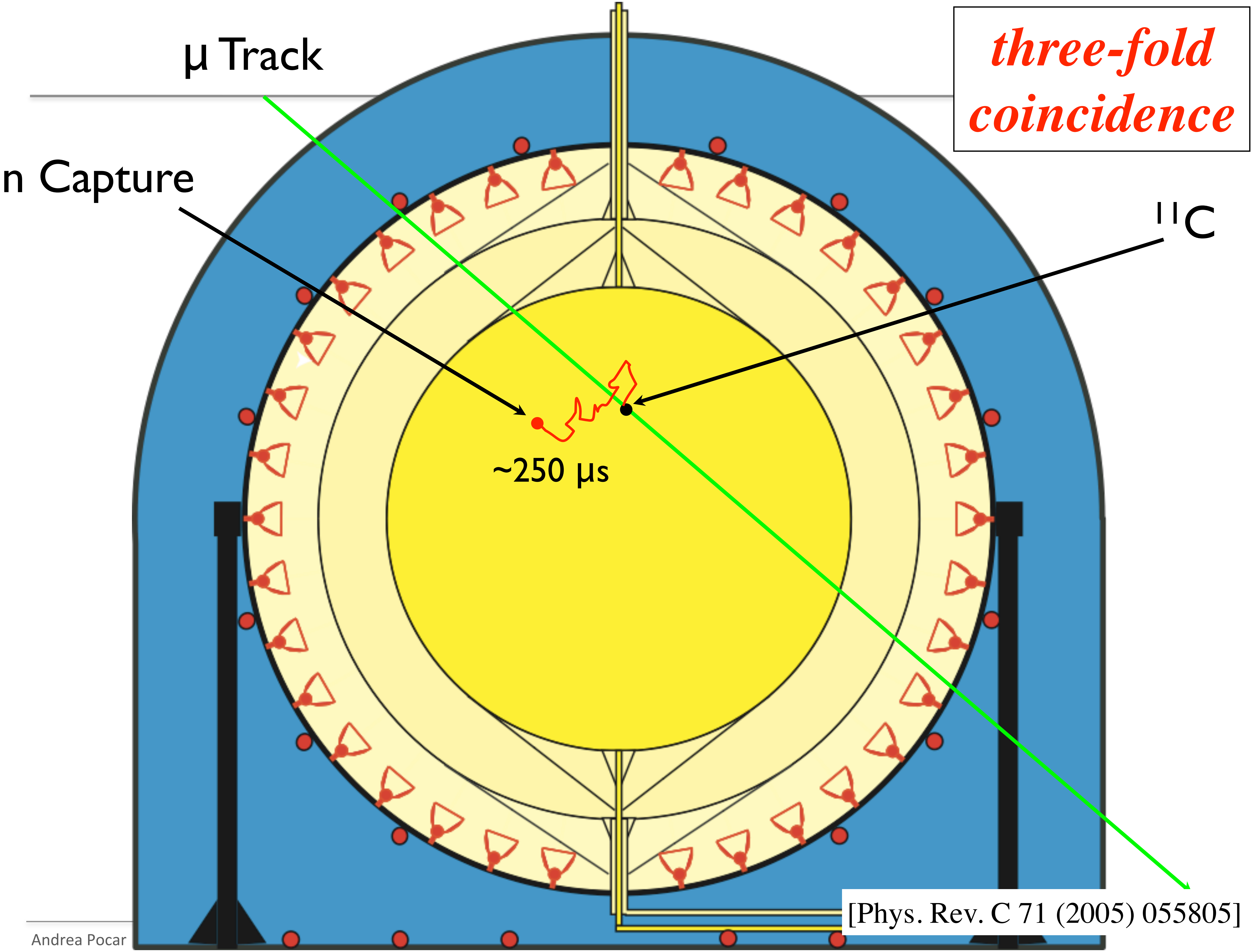
The 125 muon-neutron coincidences/day can be vetoed without excessive loss of live time by a 3-fold coincidence rejection

cosmic muon flux

[JCAP 05015 (2012)]



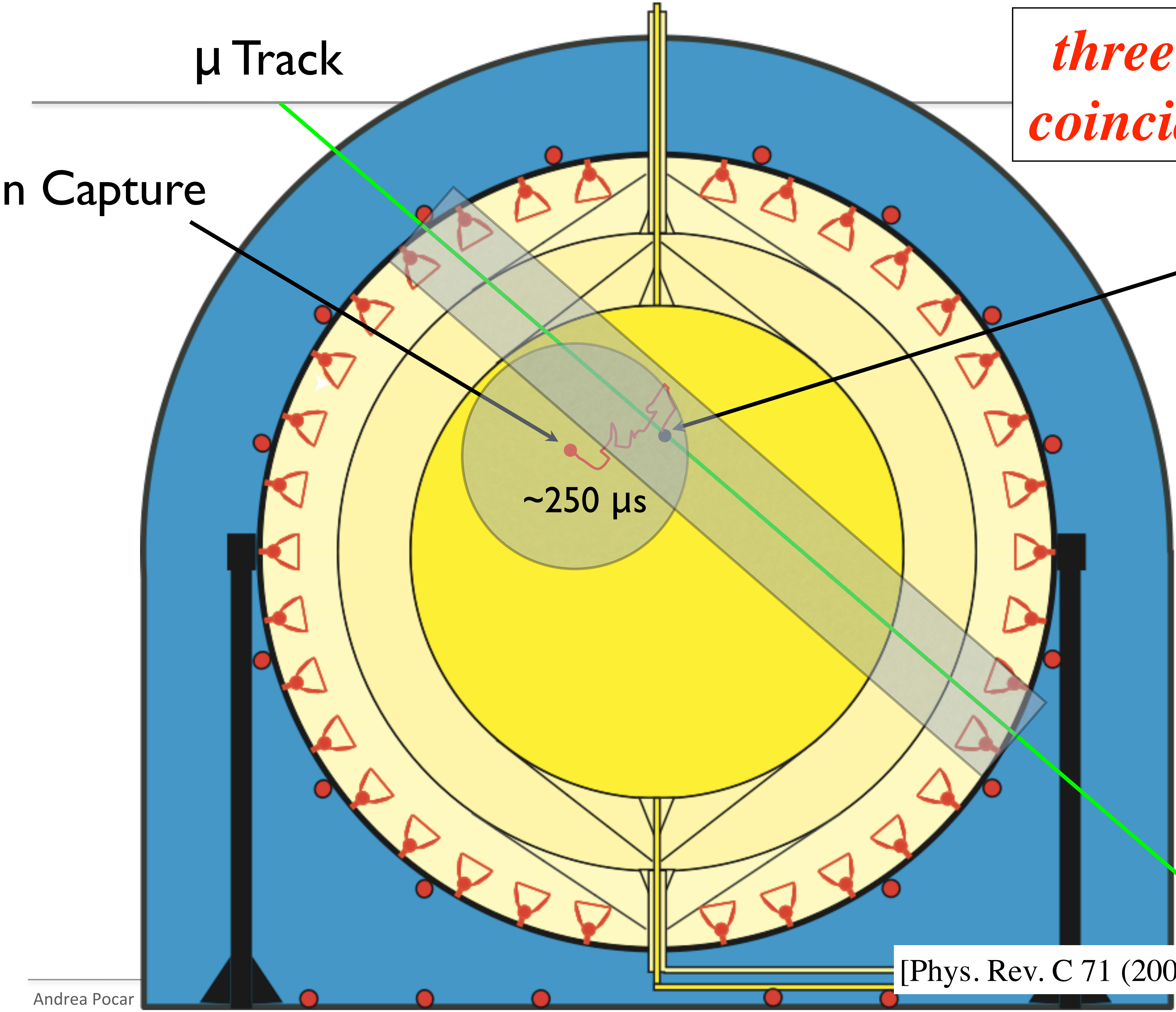
$$\text{phase:} \quad 179 \pm 6 \text{ days} \quad (\text{max on June 28})$$



three-fold coincidence

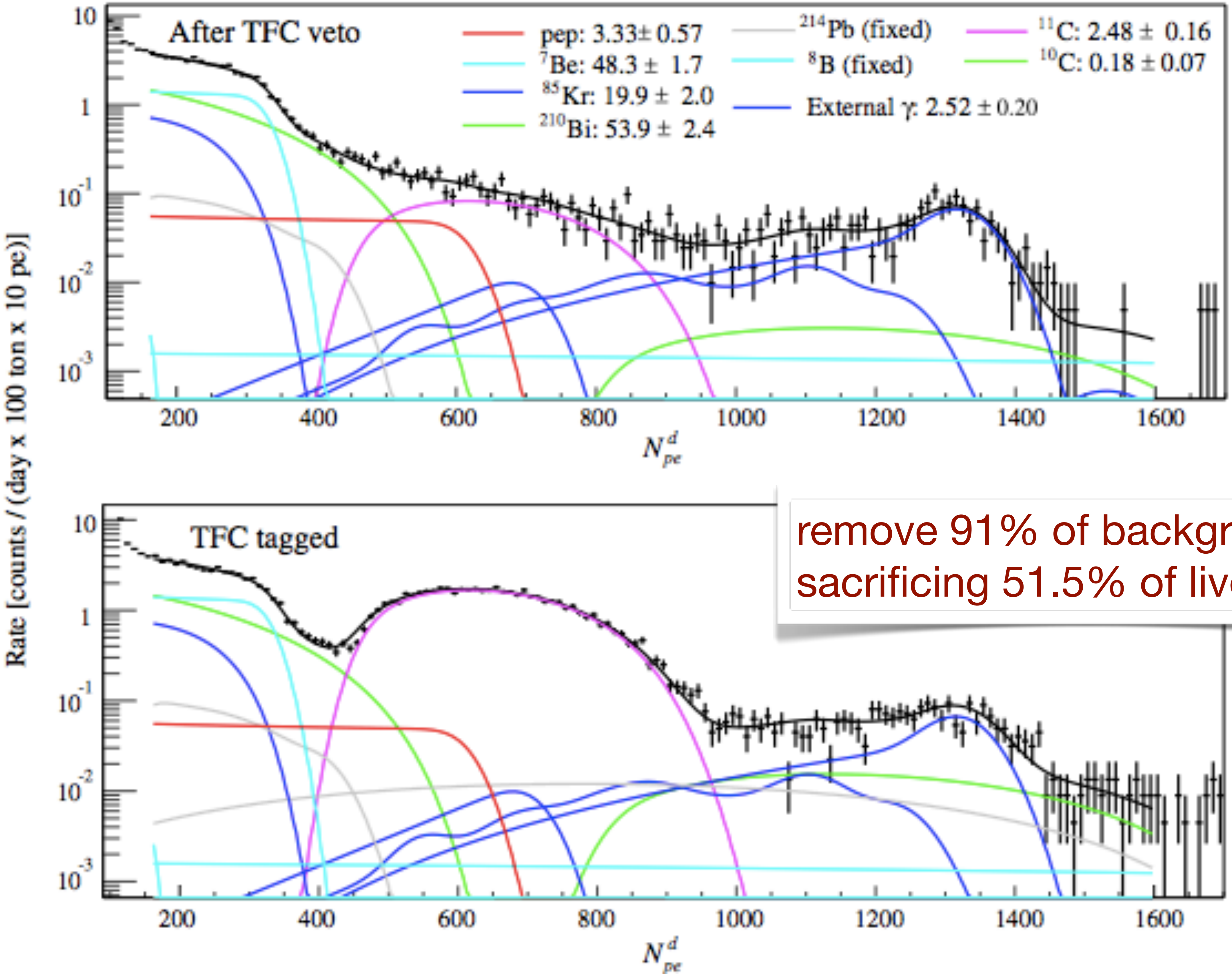
[Phys. Rev. C 71 (2005) 055805]

three-fold coincidence



[Phys. Rev. C 71 (2005) 055805]

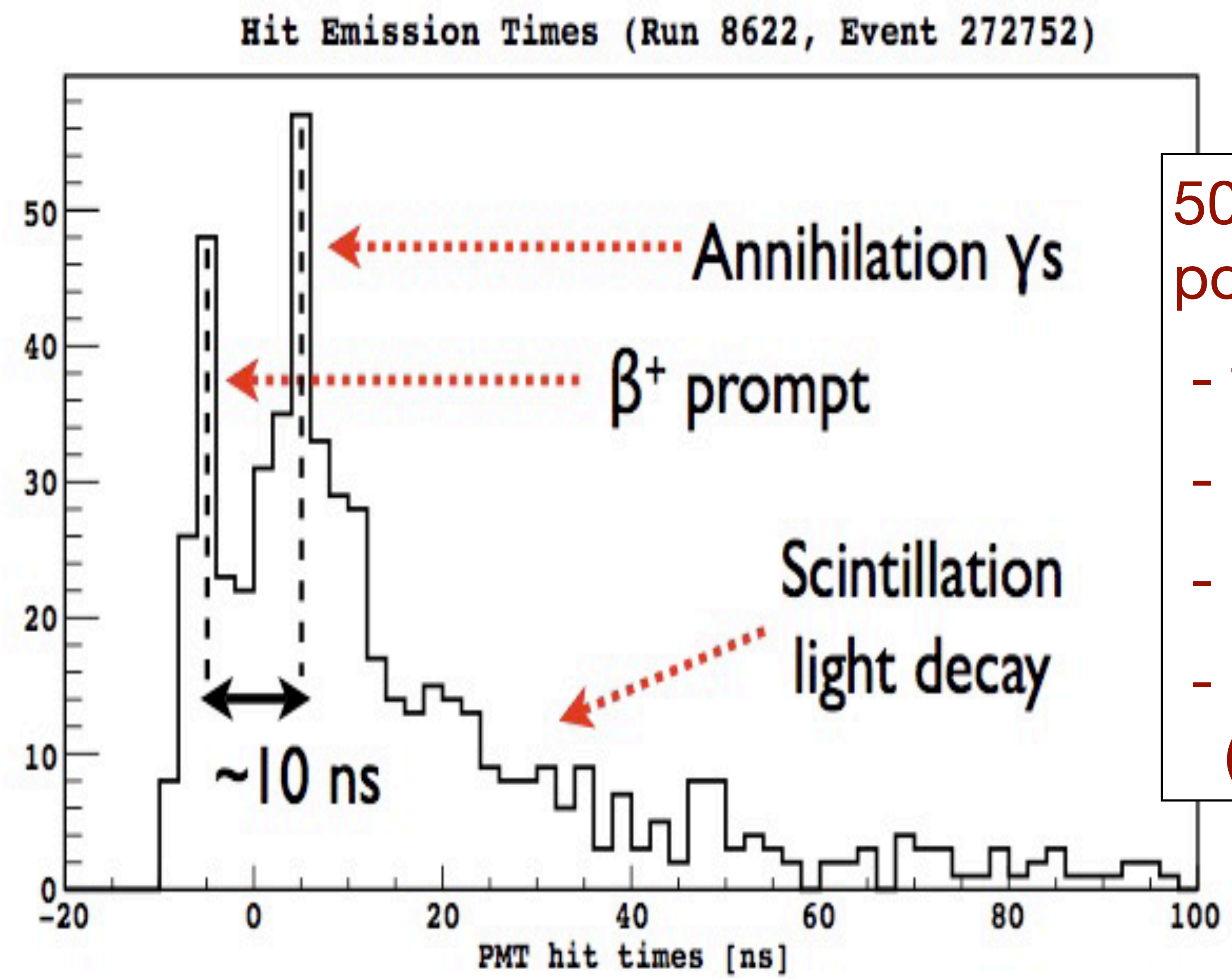
Three-fold coincidence



remove 91% of background
sacrificing 51.5% of live time

Pulse shape discrimination

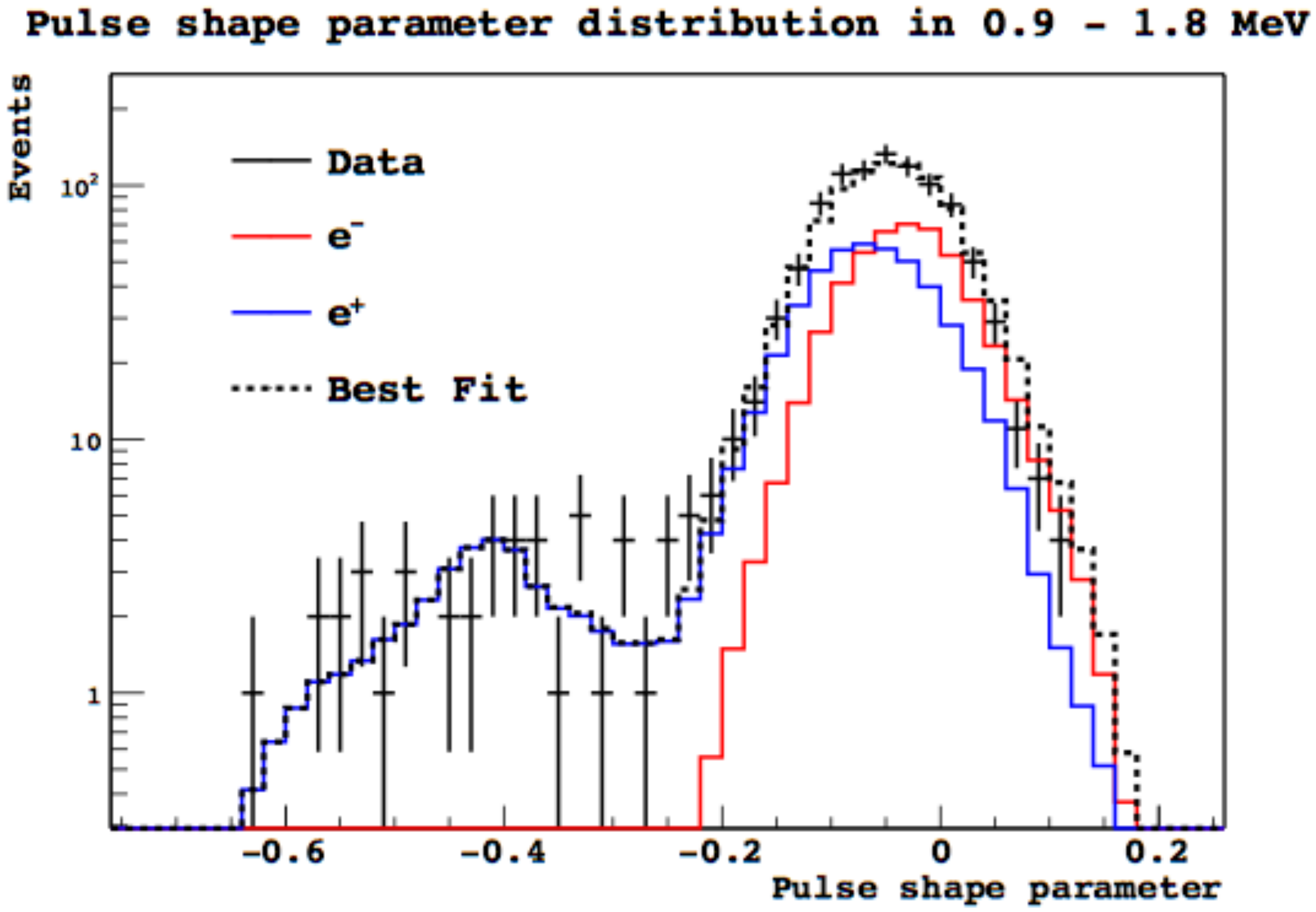
Phys. Rev. Lett. **108**, 051302 (2012)



50% of β^+ decays produce ortho-positronium ($t_{1/2} \sim 3$ ns):

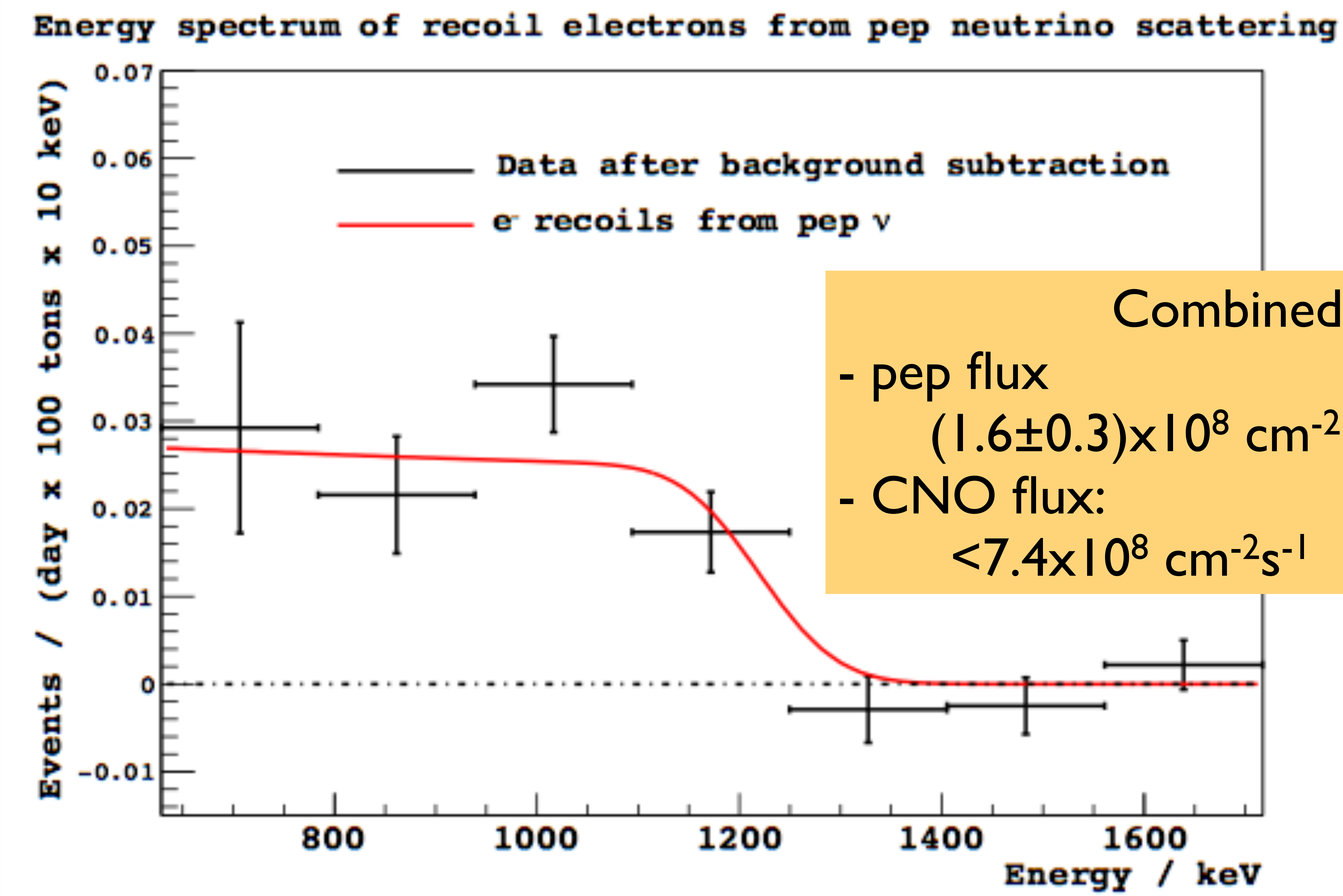
- time shift
- multi-site (gammas)
- ionization density profile
- use boosted decision tree (BDT) to optimize discrimination

Pulse shape discrimination parameter in the fit



1. Pulse shape distribution with β+ (11C,10C) and β- (other)
2. Radial distribution with external background and signal + internal backgrounds
3. Energy distribution with spectral shapes

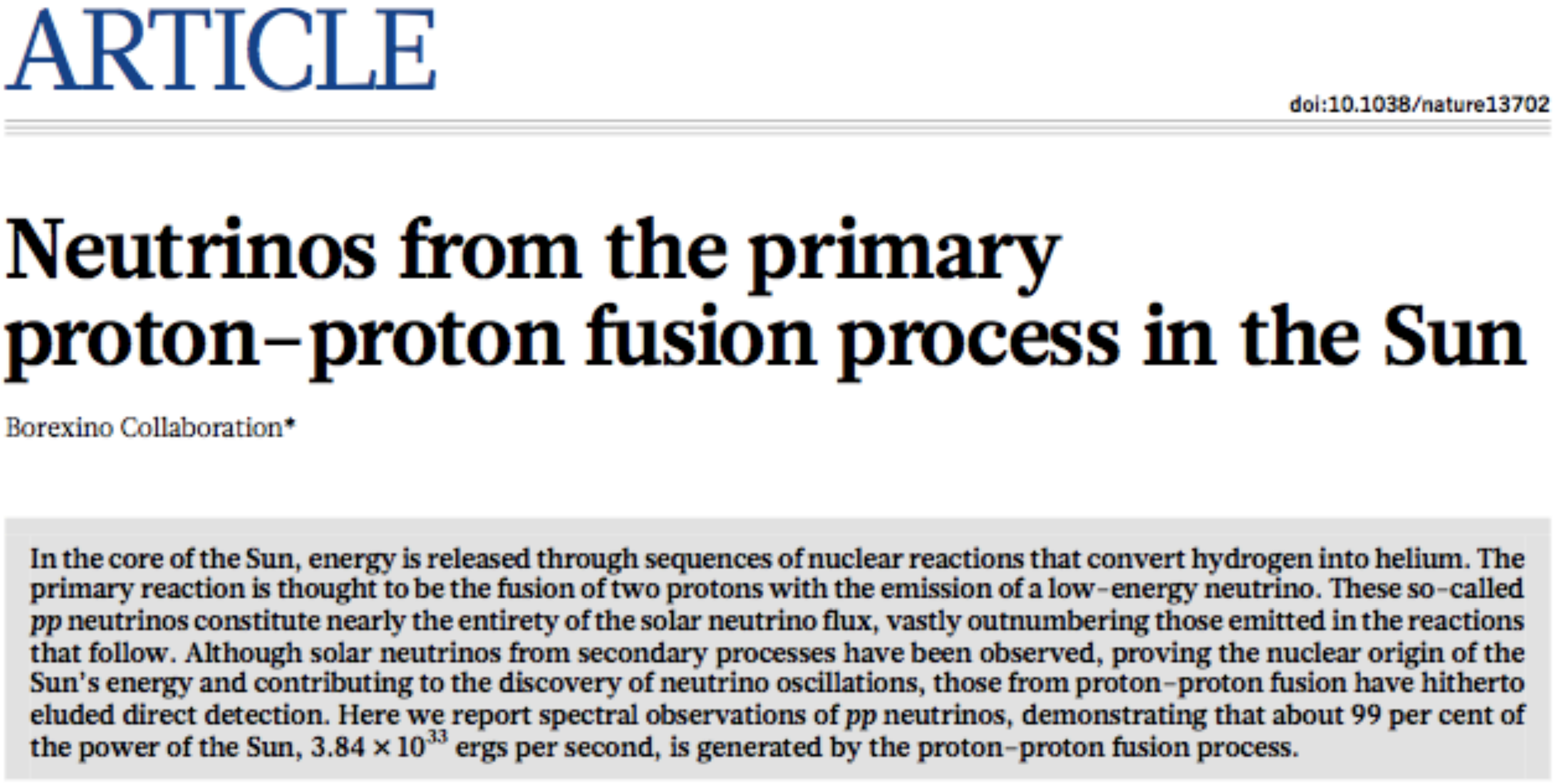
Energy Fit Residuals



Combined fit

- pep flux
  $(1.6 \pm 0.3) \times 10^{8}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- CNO flux:
  $< 7.4 \times 10^{8}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Direct measurement of *pp* solar neutrinos



ARTICLE

doi:10.1038/nature13702

Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*

In the core of the Sun, energy is released through sequences of nuclear reactions that convert hydrogen into helium. The primary reaction is thought to be the fusion of two protons with the emission of a low-energy neutrino. These so-called *pp* neutrinos constitute nearly the entirety of the solar neutrino flux, vastly outnumbering those emitted in the reactions that follow. Although solar neutrinos from secondary processes have been observed, proving the nuclear origin of the Sun's energy and contributing to the discovery of neutrino oscillations, those from proton–proton fusion have hitherto eluded direct detection. Here we report spectral observations of *pp* neutrinos, demonstrating that about 99 per cent of the power of the Sun, 3.84×10^{33} ergs per second, is generated by the proton–proton fusion process.

Nature 512, 383-366 (2014)

Why a pp solar neutrinos real time measurement?

- Probe the slowest process which sets the evolution of the Sun in 10^9 years time scale
  - 99% of energy in the Sun from

$$p + p \to d + e^+ + \nu_e + 0.42 \text{ MeV}$$

- Probe solar luminosity vs neutrino luminosity

- Probe solar variability over 10^5 years time scale

Challenges

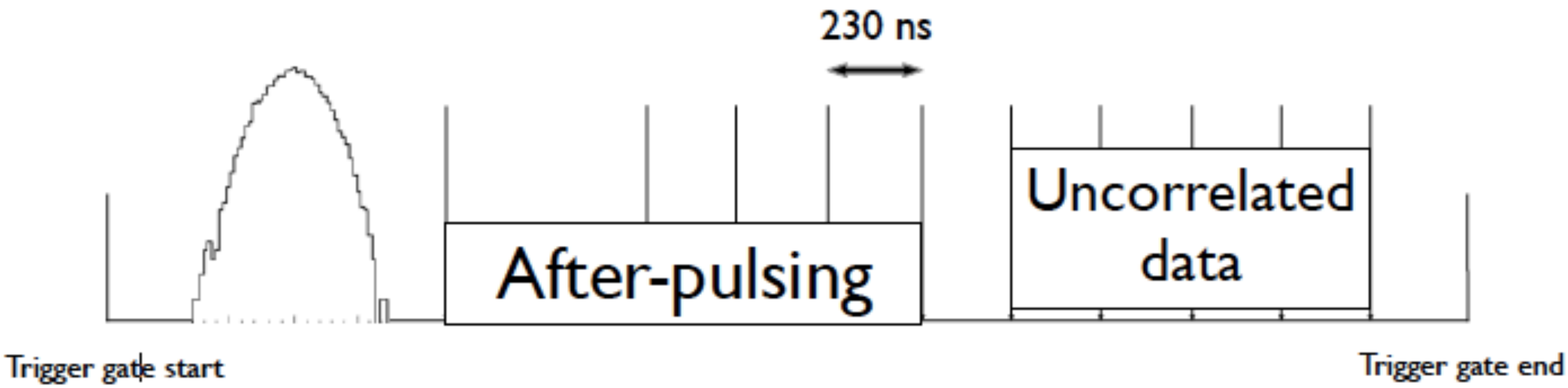
- **Rate of ^{14}C** → 3×10^{18} isotopic abundance!
  - Dominant rate component in Borexino, mainly at low energy

- **Pile-up of ^{14}C**
  - Expected to give a significant contribution at low energy

Synthetic spectrum

Pile-up may come from ^{14}C but also from other detector events

Synthetic pile-up: overlap uncorrelated data with regular events



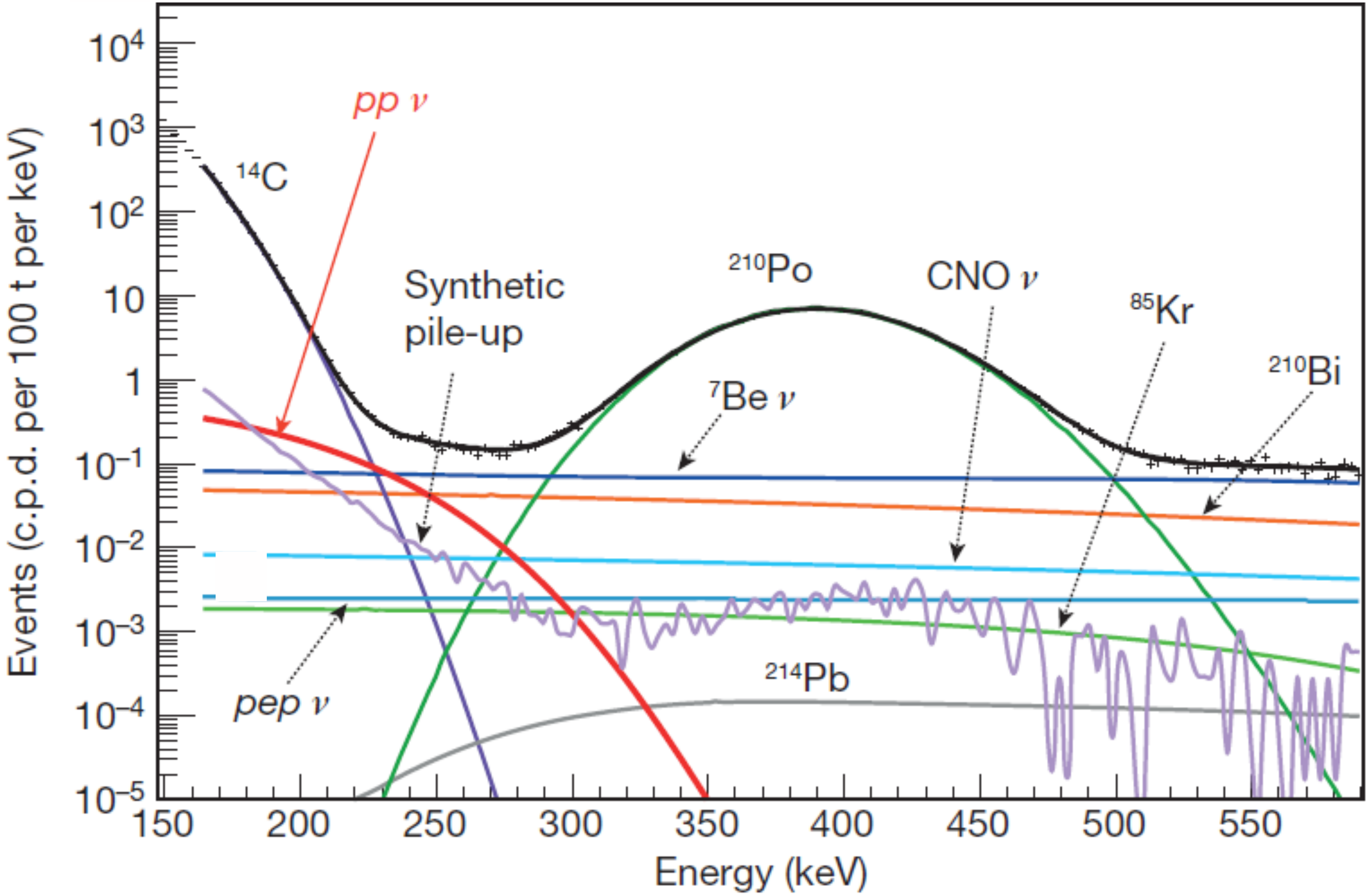
Result used to constrain rate of pile-up in final fit

Nature 512, 383-366 (2014)

pp neutrinos

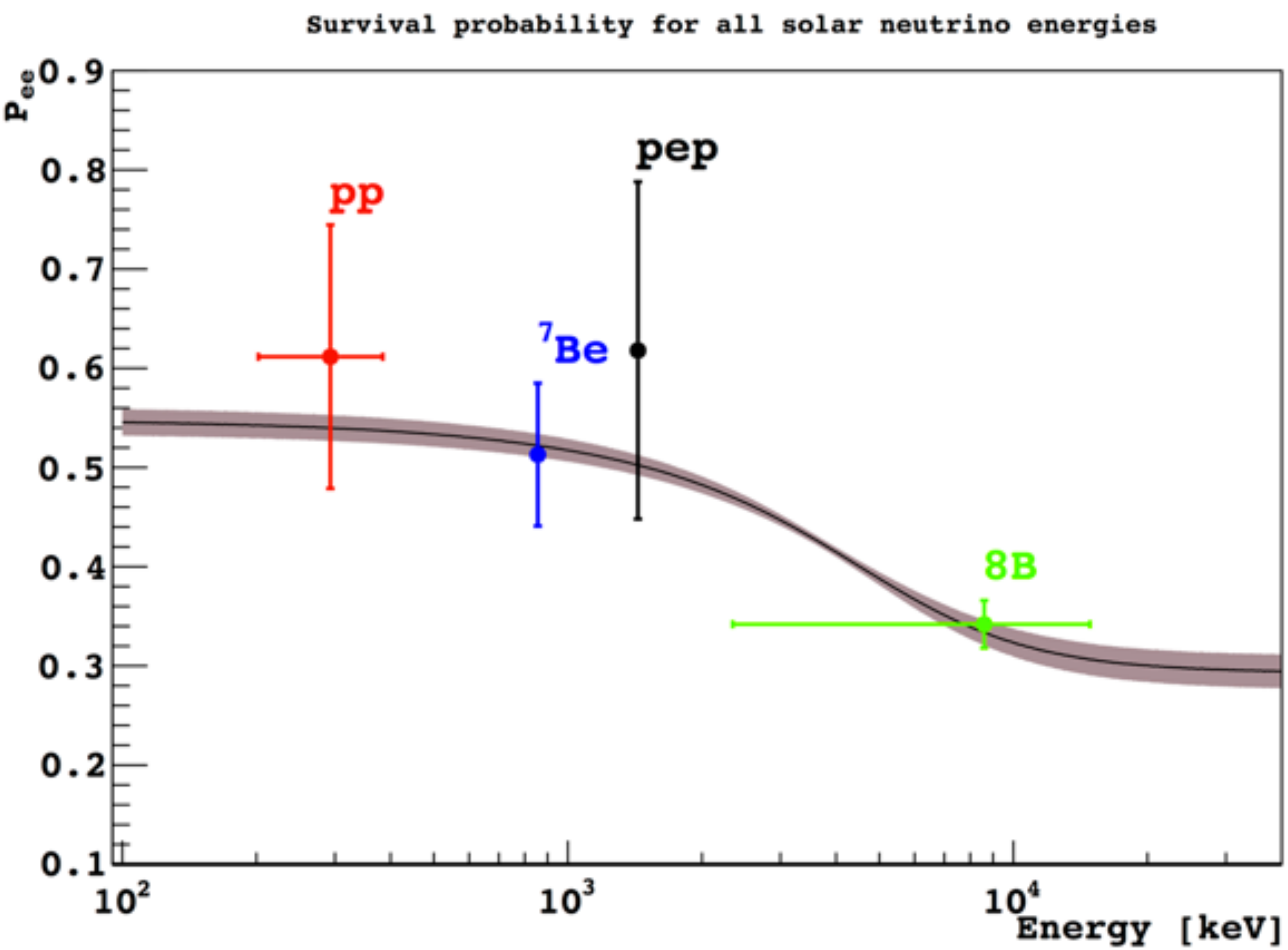
pp: 144 ± 13 *(stat)* cpd/100 t

(pp expected : 131 cpd/100ton)



Nature **512**, 383-386

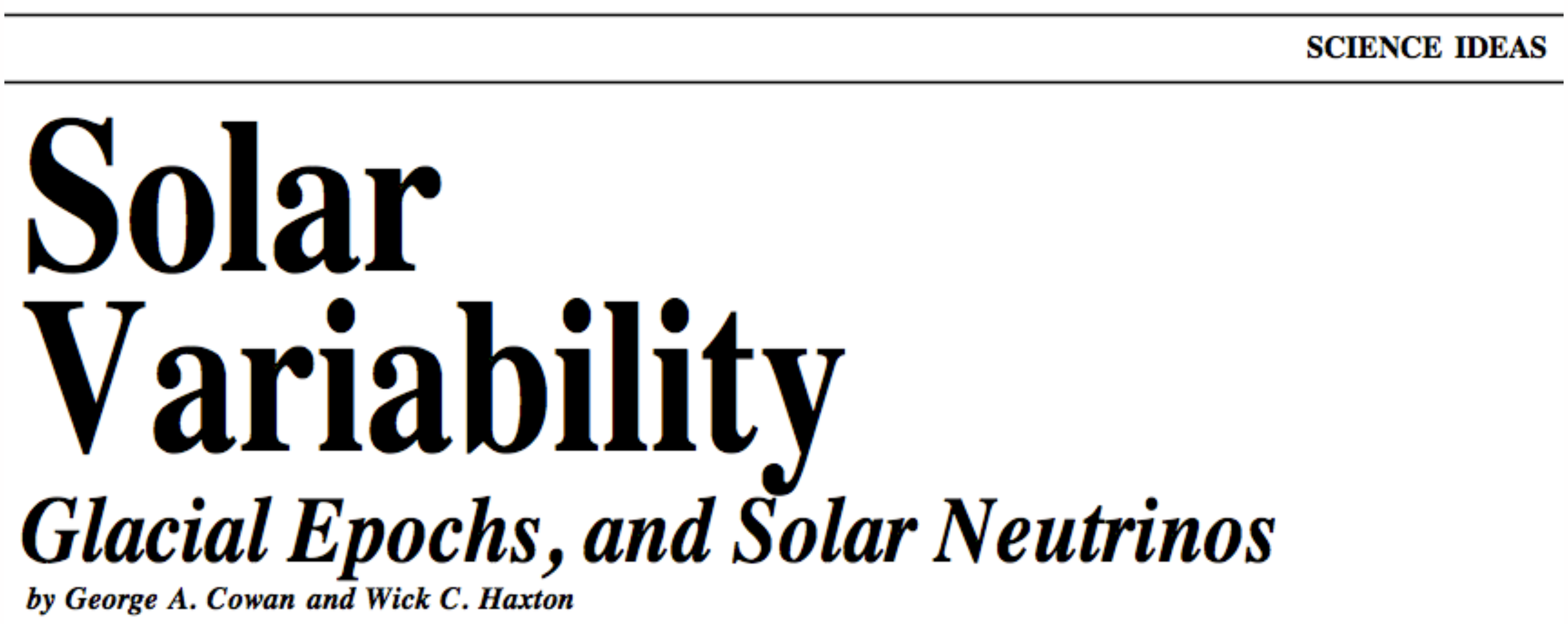
Interpretation I: neutrino survival probability



$$P_{ee} = \begin{cases} 0.612 \pm 0.133 & \text{measured} \\ 0.543 \pm 0.013 & \text{expected} \end{cases}$$

Interpretation II: solar stability

Check the time stability of the Sun (time scale 10^5 years), which is a crucial assumption in the Standard Solar Model



SCIENCE IDEAS

Solar Variability

Glacial Epochs, and Solar Neutrinos

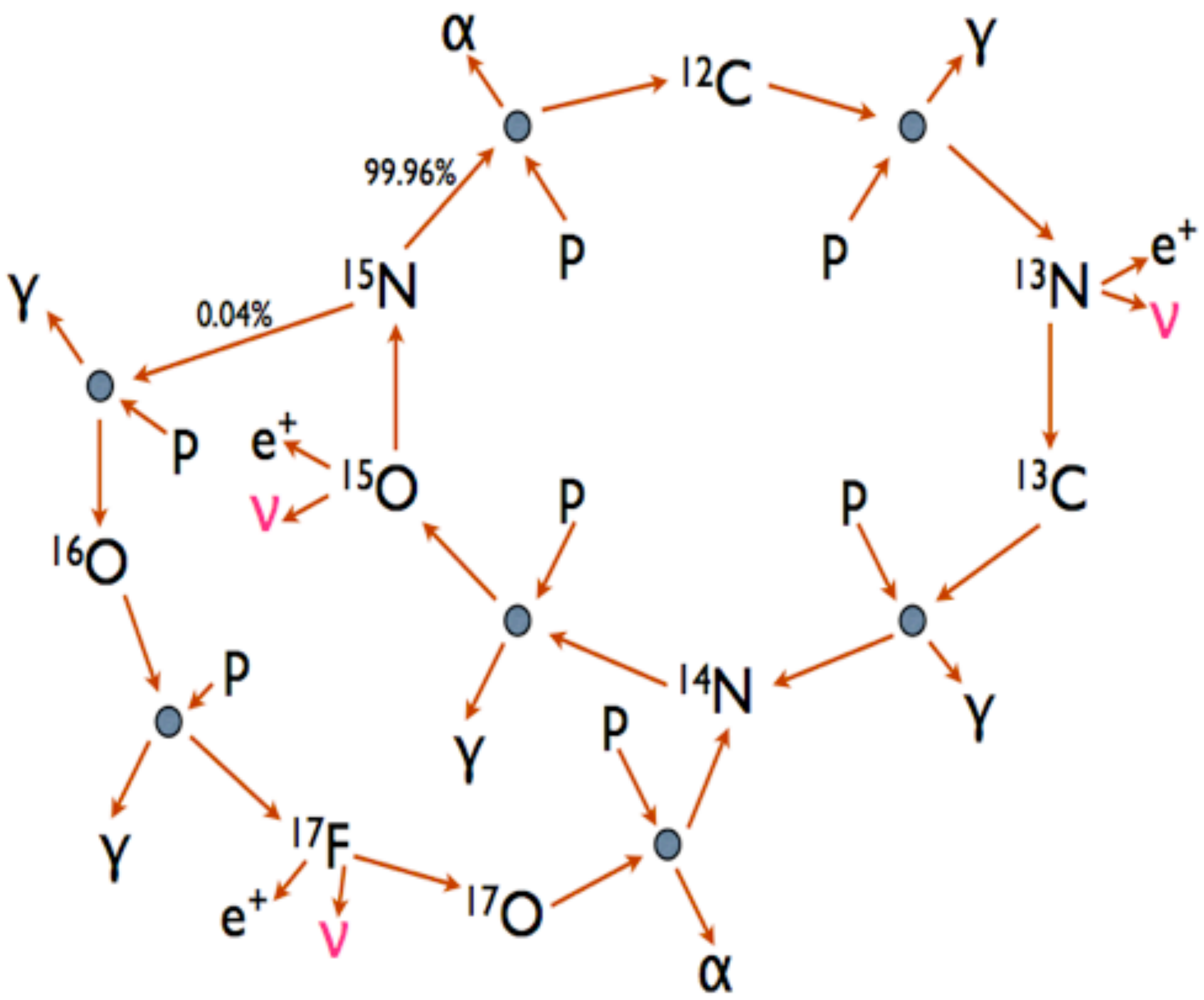
by George A. Cowan and Wick C. Haxton

[Los Alamos Science, 1982]

A few backgrounds facts

- <1 bulk radon event / year (in 100 tons)
- Th-232, U-238 concentration in the scintillator $\sim$ 1:10^{19}
- Trigger rate set by C-14 contamination (3x10^{18} isot. ab.)

CNO solar neutrinos



- A direct measurement of the CNO neutrinos rate could help solve the latest controversy surrounding the Standard Solar Model

- One fundamental input of the Standard Solar Model is the metallicity of the Sun - abundance of all elements above Helium

- Solar neutrinos can help resolve
  ^{7}Be (12% difference)
  CNO (>30% difference)

Solar Model Chemical Controversy

Bahcall, Serenelli and Basu, AstropJ 621, L85(2005)

Φ ($cm^{-2}s^{-1}$)	*pp* ($\times10^{10}$)	^{7}Be ($\times10^{9}$)	^{8}B ($\times10^{6}$)	^{13}N ($\times10^{8}$)	^{15}O ($\times10^{8}$)	^{17}F ($\times10^{6}$)
BS05 GS 98	5.99	4.84	5.69	3.07	2.33	5.84
BS05 AGS 05	6.05	4.34	4.51	2.01	1.45	3.25
Δ	+1%	-10.0%	-21.00%	-35.0%	-38.0%	-44.0%
σ SSM	±1%	±5%	±16%	±15%	±15%	±15%

Helioseismology incompatible with low metallicity solar models. Could be resolved by measuring CNO neutrinos

Grevesse and Sauval, Space Sci. Rev. **85**, 161 (1998)

Asplund, Grevesse and Sauval, Nucl. Phys. A **777**, 1 (2006)

Next for Borexino

- **Phase II**: about 860 livedays since Dec 11th 2011 (very low ^{85}Kr and low ^{210}Bi)
- **Calibration campaign**
- **Scintillator Purification**
- **Main goal**: improve sensitivity to pep and CNO neutrinos, neutrino effective magnetic moment

- **SOX (end of 2016)**
  short baseline oscillations with 150 kBq Ce-144 anti-neutrino source placed underneath the detector

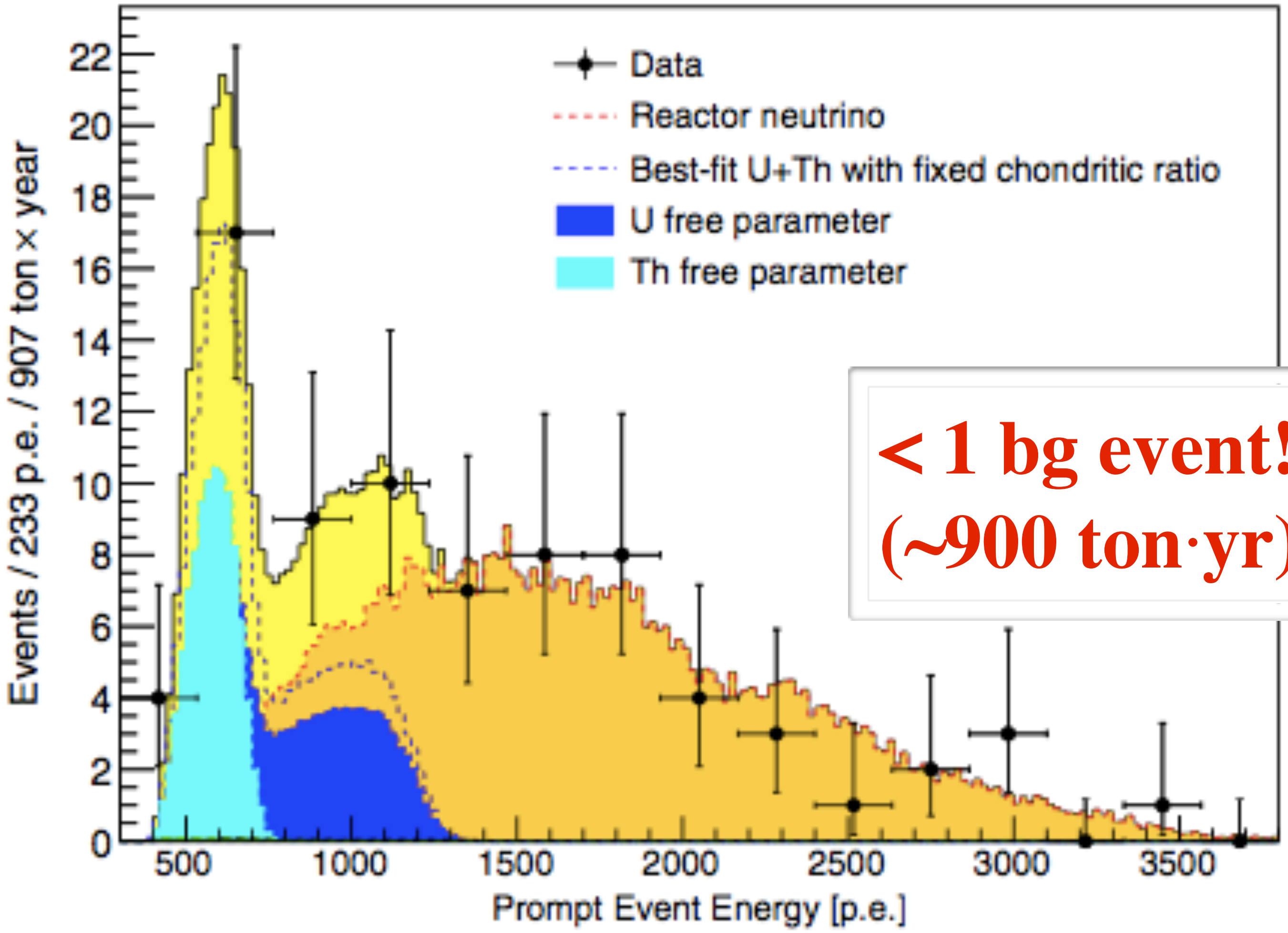
Geo-neutrinos

- Anti-neutrinos associated with beta decays in the Earth
- Detected via IBD, characteristic coincidence
    - ^{232}Th and ^{238}U chains
    - ^{40}K   (below IBD threshold)

- Observed by two experiments:
    - First reported by KamLand (’05, then in ’13)
    - Borexino published in ’10, ’13, ’15

geo-neutrino observation (2056 days)

extremely low background allows for a measurement even with low statistics (null hypothesis excluded at 5.9σ)

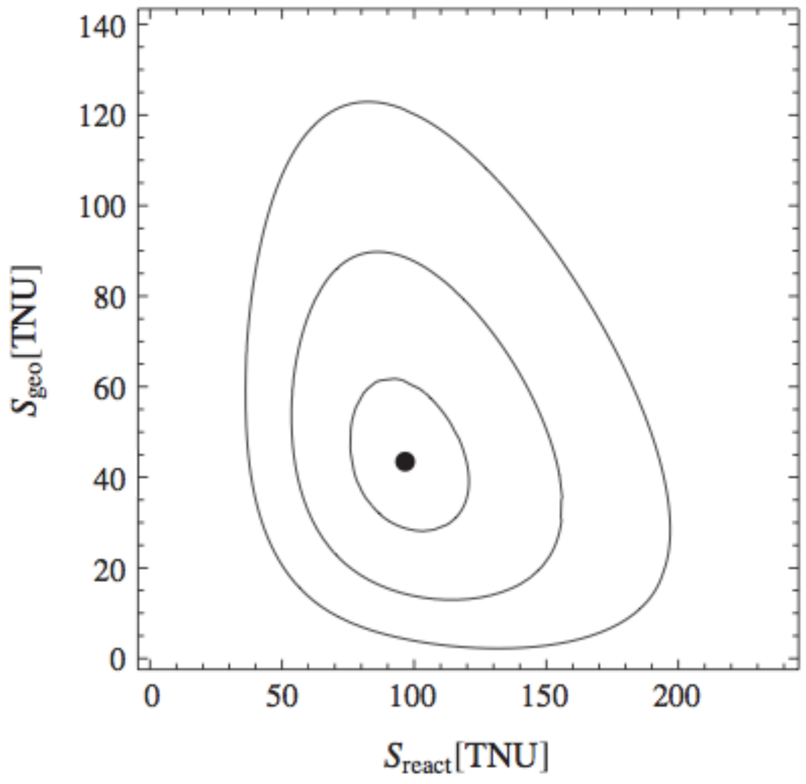


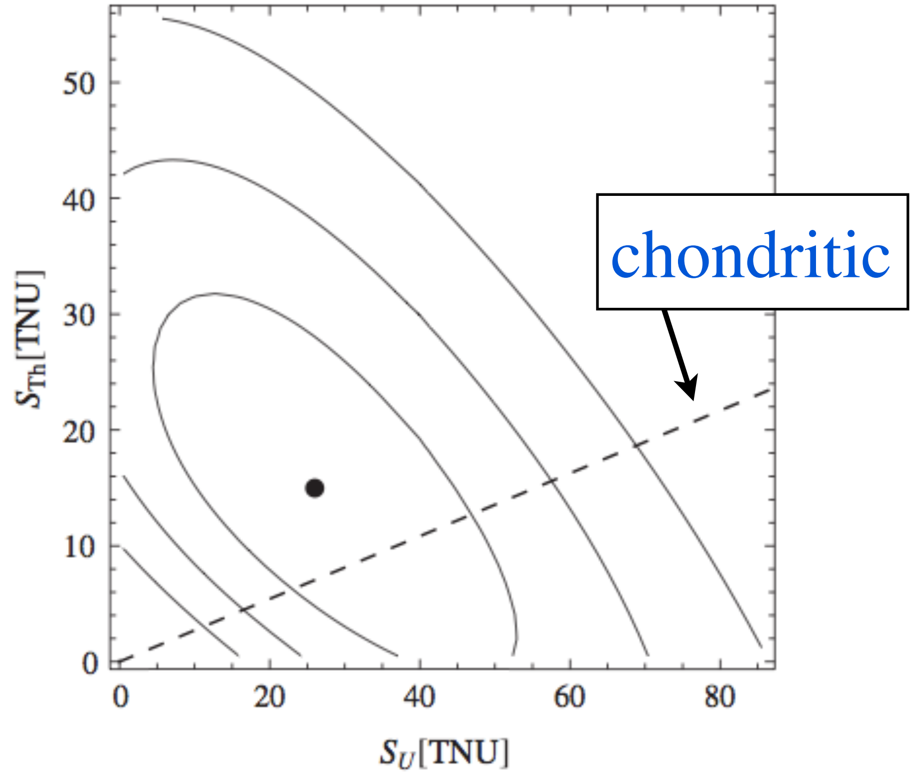
< 1 bg event! (~900 ton·yr)

$$\text{Sgeo} = 23.7^{+6.5}_{-5.7}(\text{stat})^{+0.9}_{-0.6}(\text{sys})$$

(assuming Th:U chondritic ratio = 3.9)

1 TNU = 1 event/yr/10^{32} protons)





the Borexino Collaboration

INFN

Milano

München

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK
Heidelberg

Hamburg

Mainz

Gran Sasso

Perugia

Genova

Napoli

TU Dresden

Jagiellonian
Kraków

Virginia Tech

Houston

Paris

Moscow

JINR
Dubna

Los Angeles

Princeton

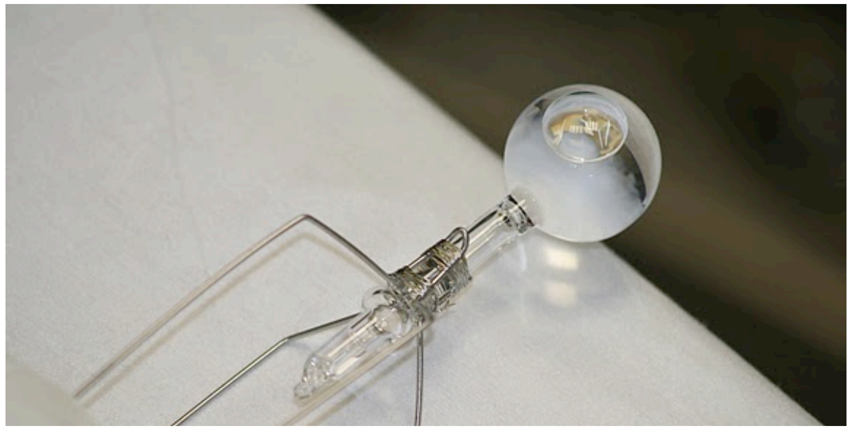
UMass
Amherst

St. Petersburg

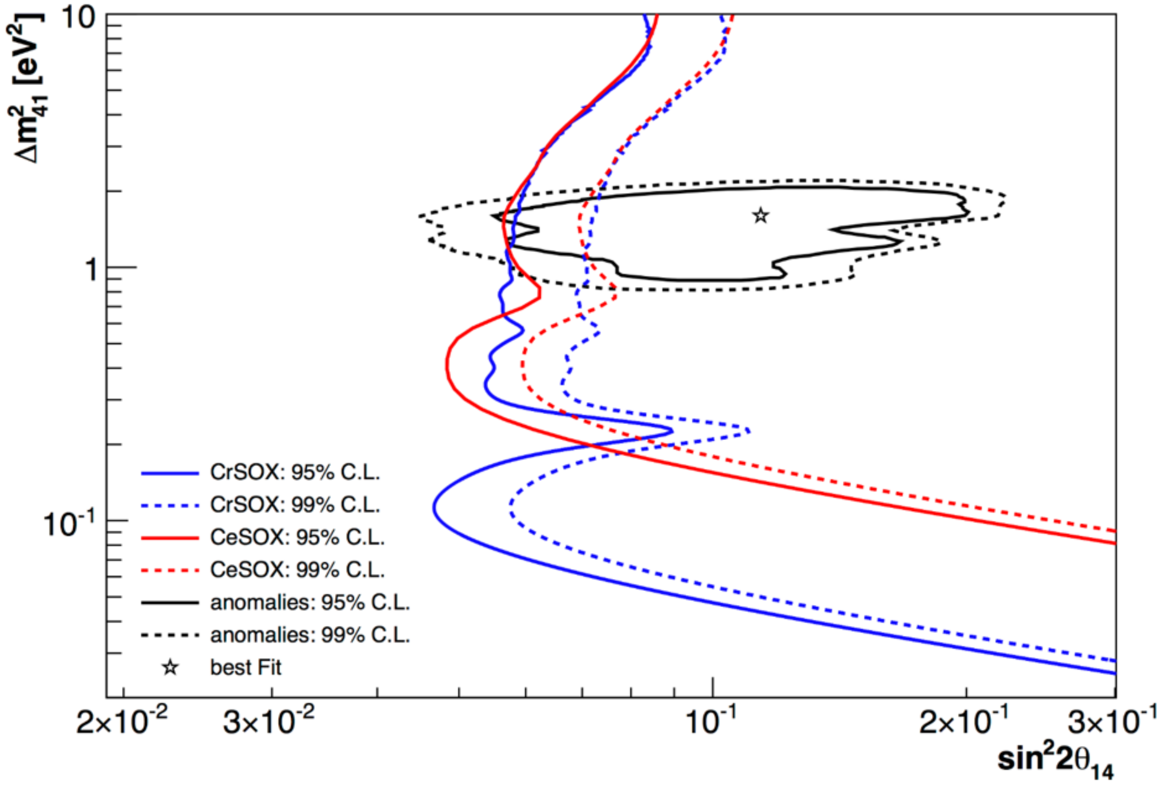
Kurchatov
Moscow

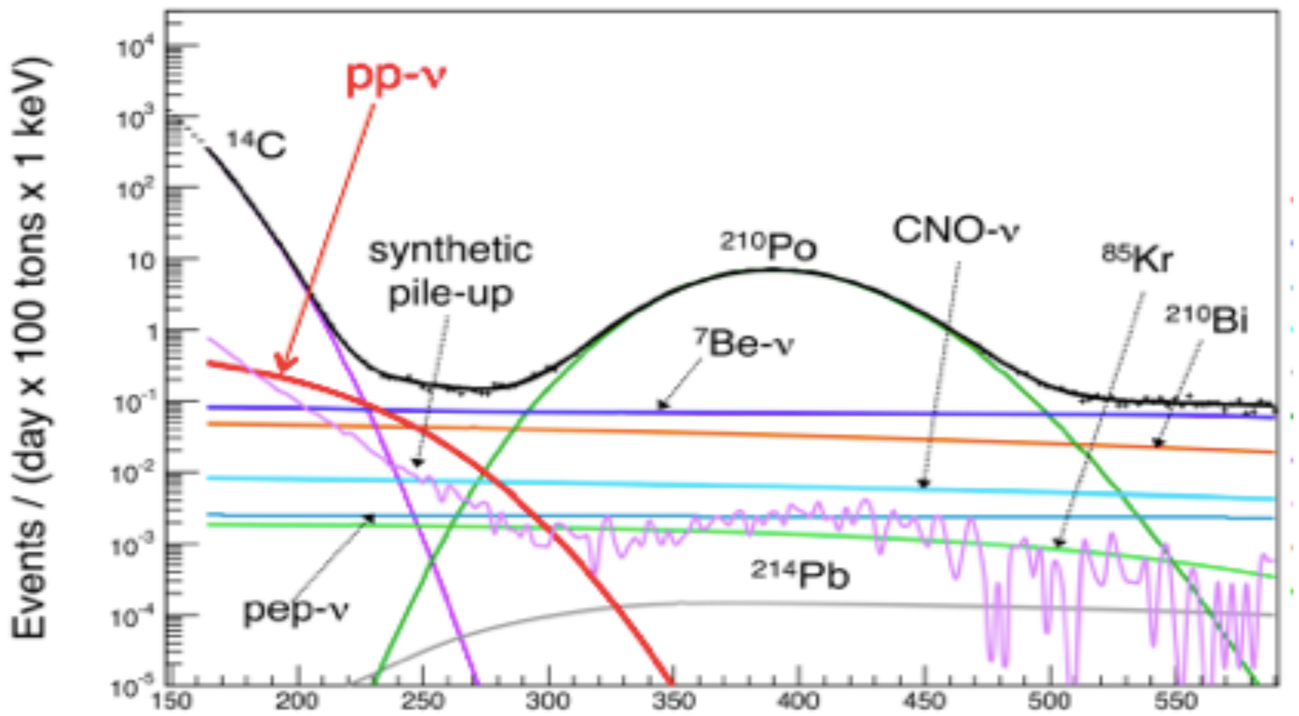
Summary

stay hungry, my friend



- With the first direct measurement of the pp flux, Borexino has almost completed the entire solar neutrino spectroscopy, strengthening our understanding of oscillations and of the Sun
- A possible measurement of CNO neutrinos would give us key knowledge of the Sun's metallicity
- Borexino now plans a new calibration campaign and further scintillator purification
- The SOX run with Ce-144 (end of 2016) will probe neutrino oscillations at $\Delta m^2 \sim eV^2$ (sterile ν's)





extras

^{8}B solar neutrinos at low threshold

$$R(^8B) = 0.22 \pm 0.04\ (stat) \pm 0.01\ (syst)\ \ \text{cpd}/100\ t$$

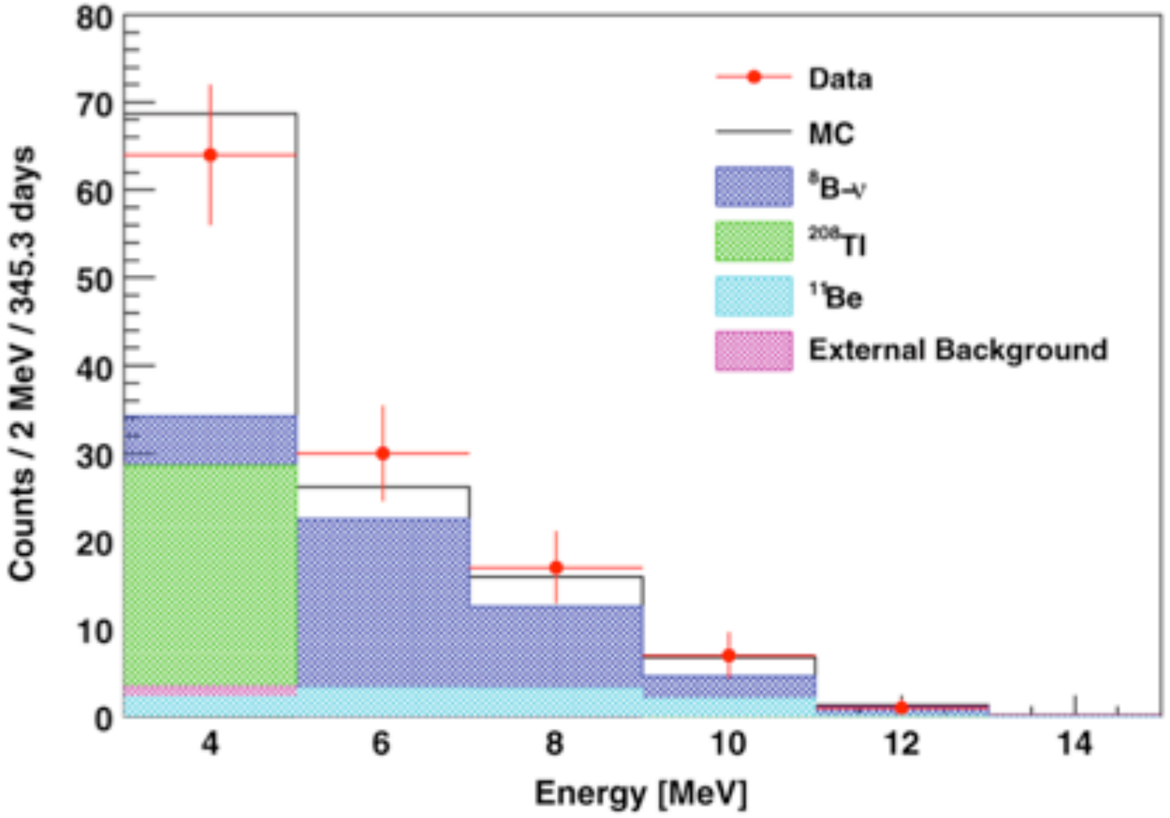
First measurement of P_{ee} in vacuum (^{7}Be ν) and matter-enhanced regime (^{8}B ν) in the same detector

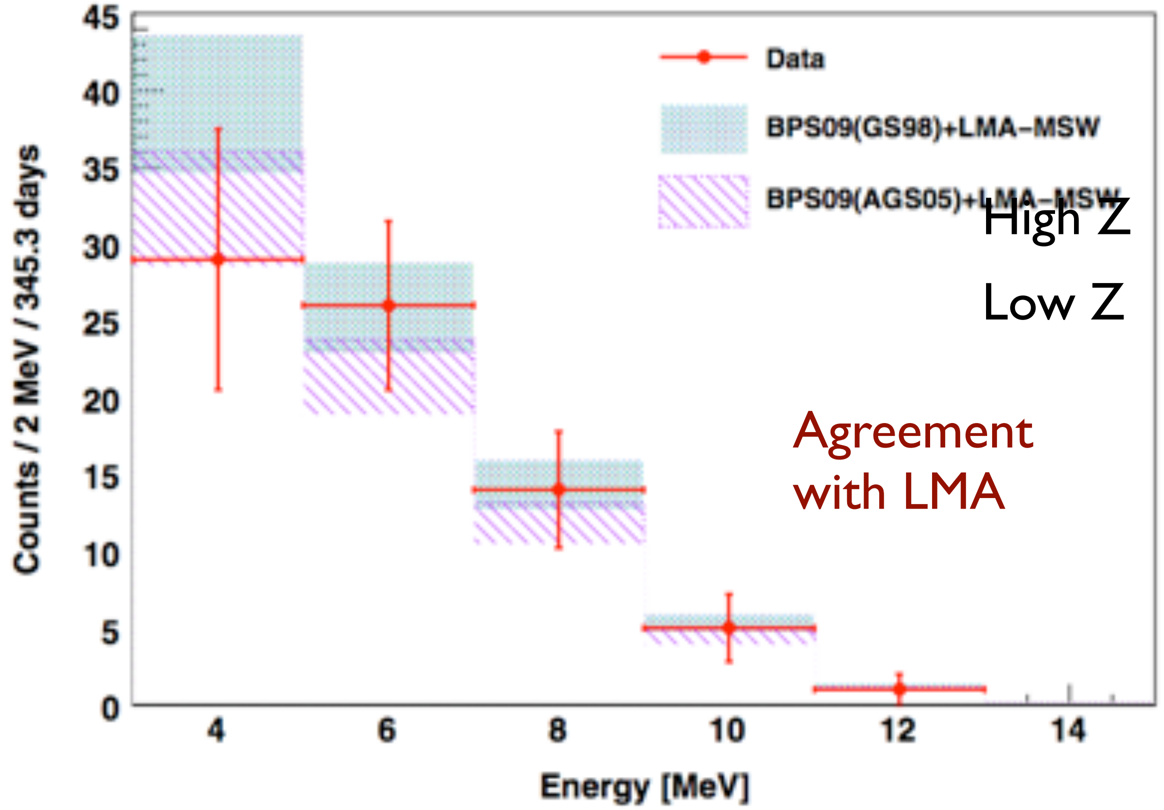
$$P_{ee} = 0.29 \pm 0.10$$

TABLE IV. Systematic errors.

Source	$E > 3$ MeV		$E > 5$ MeV	
	σ_+	σ_-	σ_+	σ_-
Energy threshold	3.6%	3.2%	6.1%	4.8%
Fiducial mass	3.8%	3.8%	3.8%	3.8%
Energy resolution	0.0%	2.5%	0.0%	3.0%
Total	5.2%	5.6%	7.2%	6.8%

Phys Rev D 82, 0330006 (2010)





High Z

Low Z

Agreement with LMA

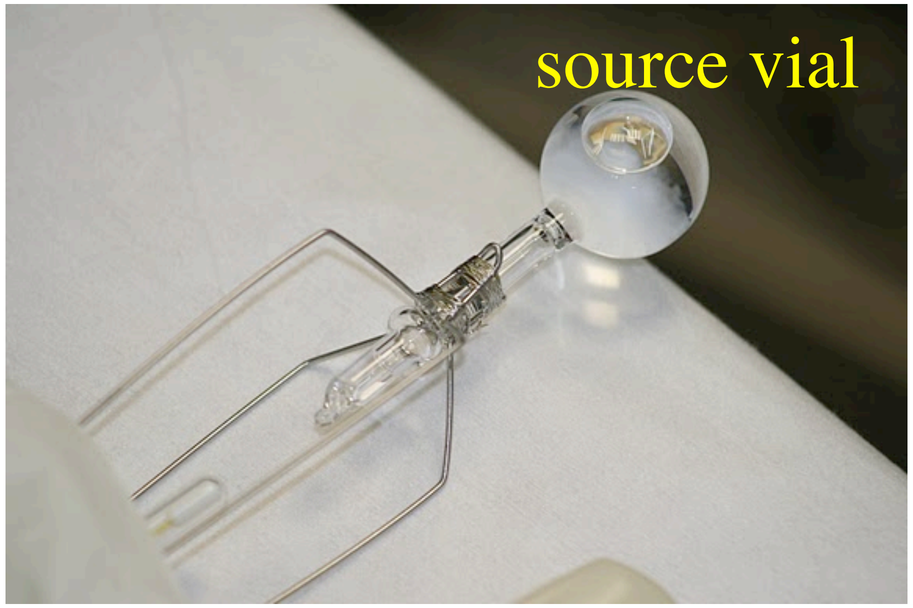
calibration sources

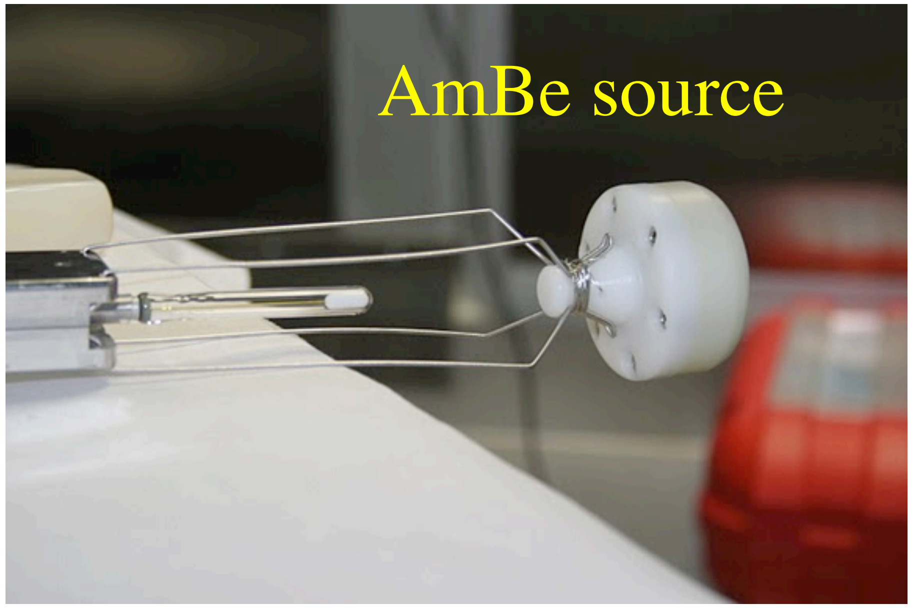
	γ								β		α	n		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n +^{12}C	n+Fe
energy (MeV)	0.122	0.165	0.279	0.514	0.834	1.1	1.1, 1.3	1.4	0.15	3.2		2.226	4.94	~7.5

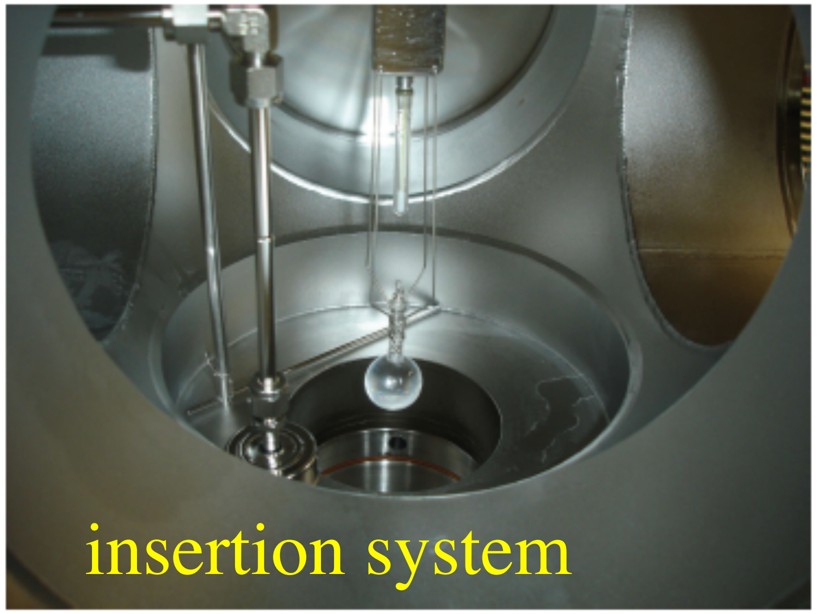
spiked water vial

spiked scintillator vial

AmBe







detector calibrations

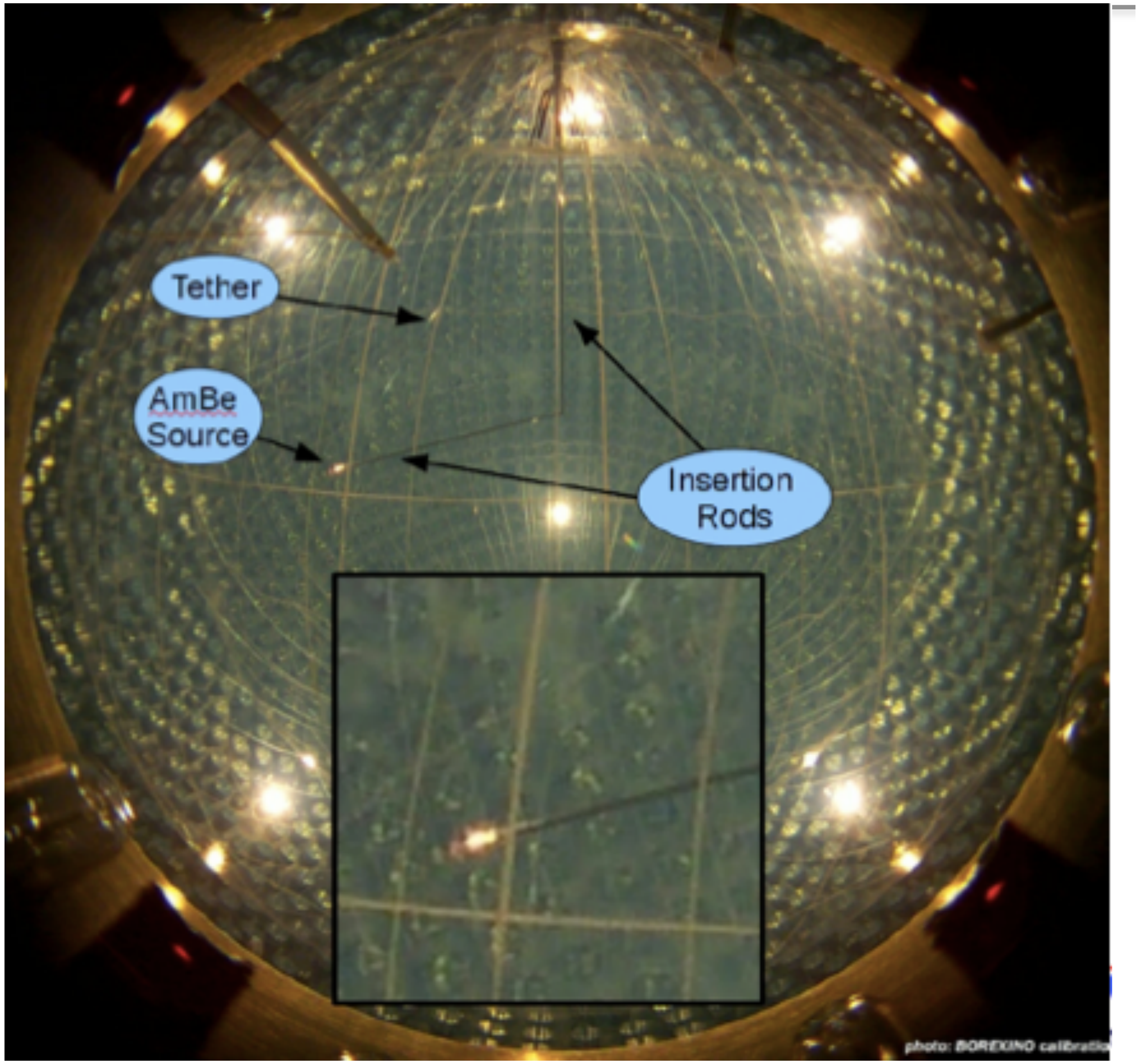
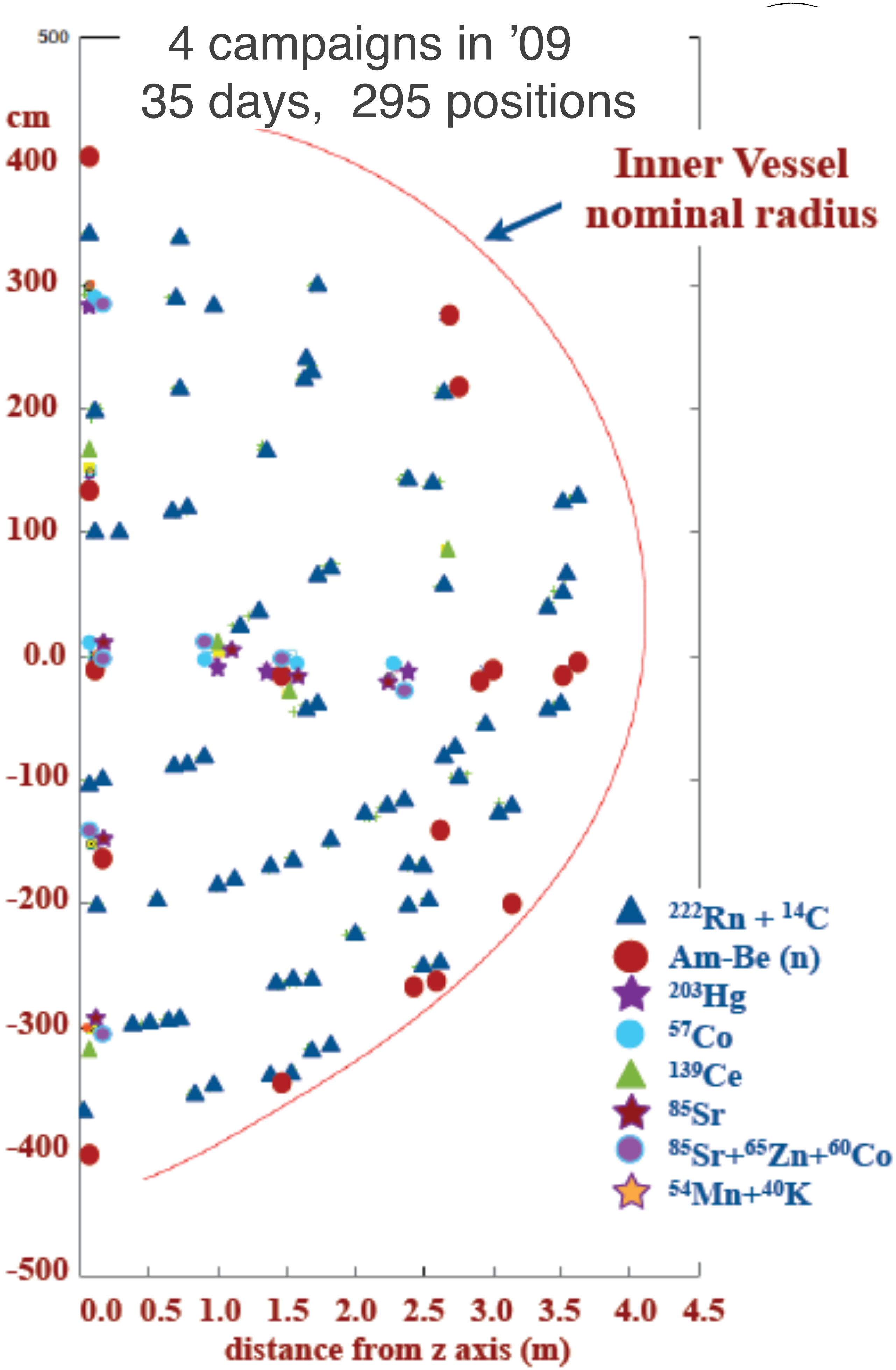


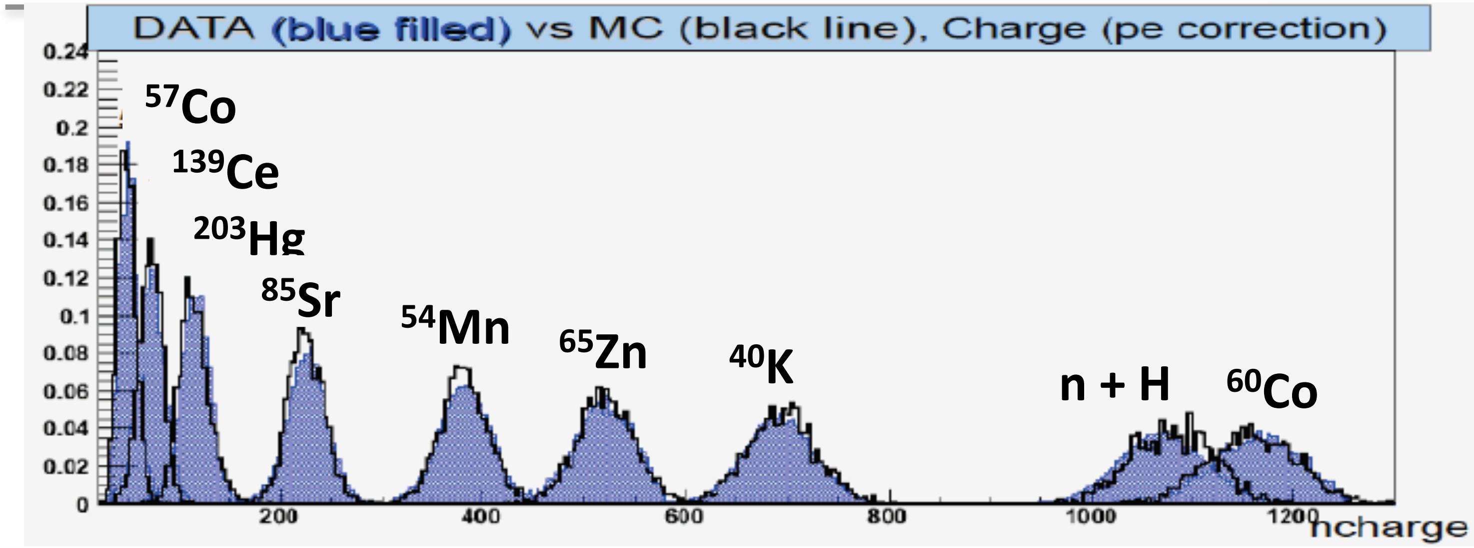
photo: BOREXINO calibratio

- position known with ~2 cm accuracy with 7 CCD cameras mounted on the steel sphere
- external γ source deployed in water tank ('10)



4 campaigns in '09
35 days, 295 positions

position and energy calibration



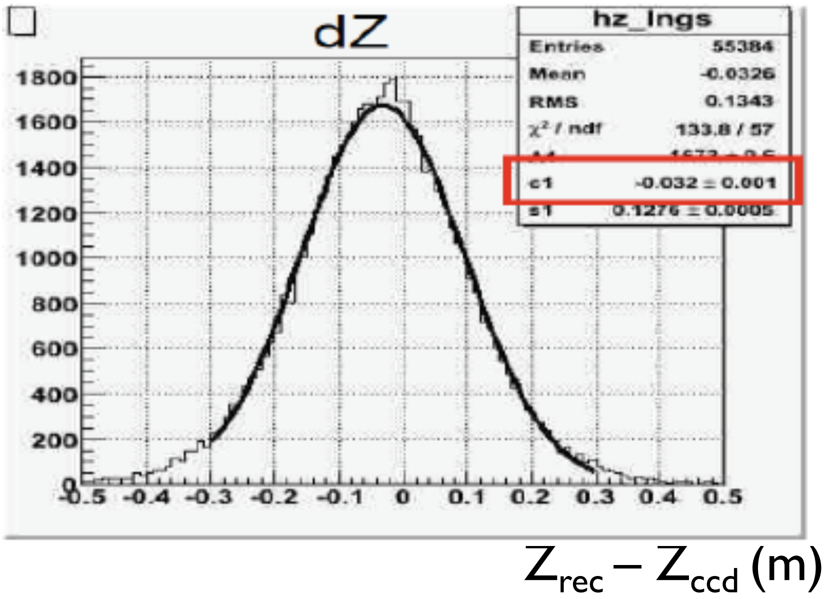
Study light yield, quenching, position variation.

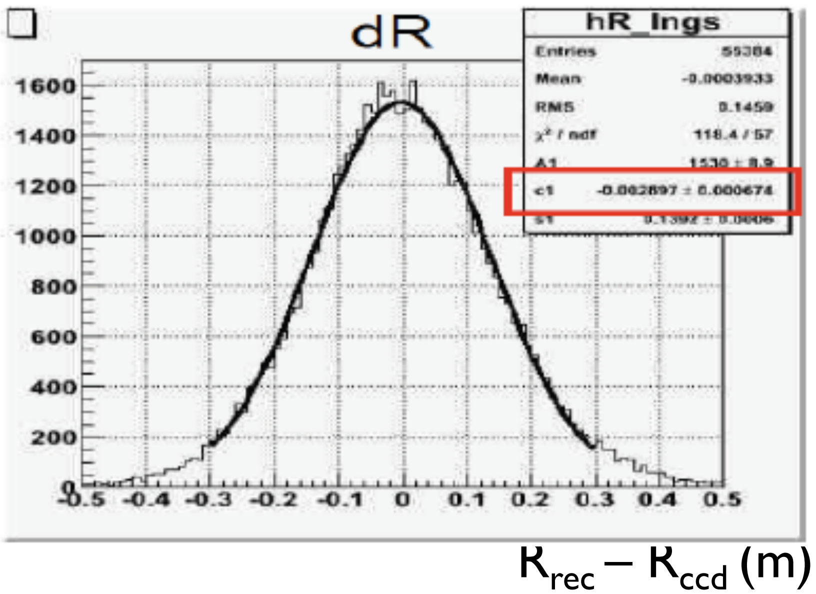
→ *Data-MC mean light yields agree to 1% in F.V.*

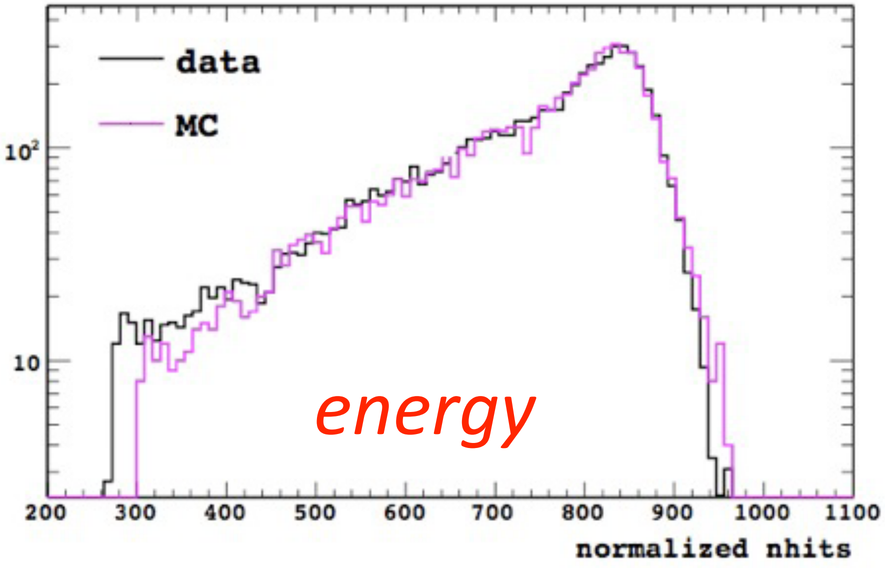
Measure position resolution: 10 – 12 cm

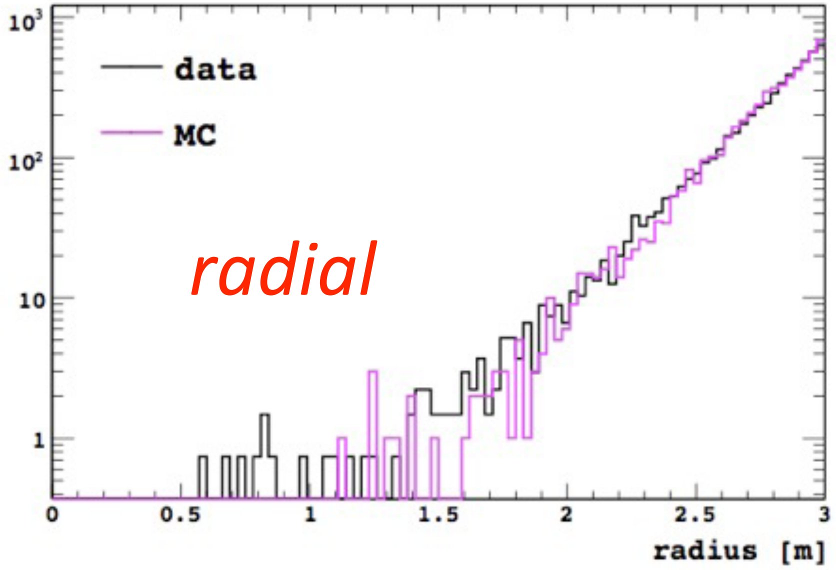
→ *Fiducial Volume:*

$1.0^{+0.005}_{-0.013}$





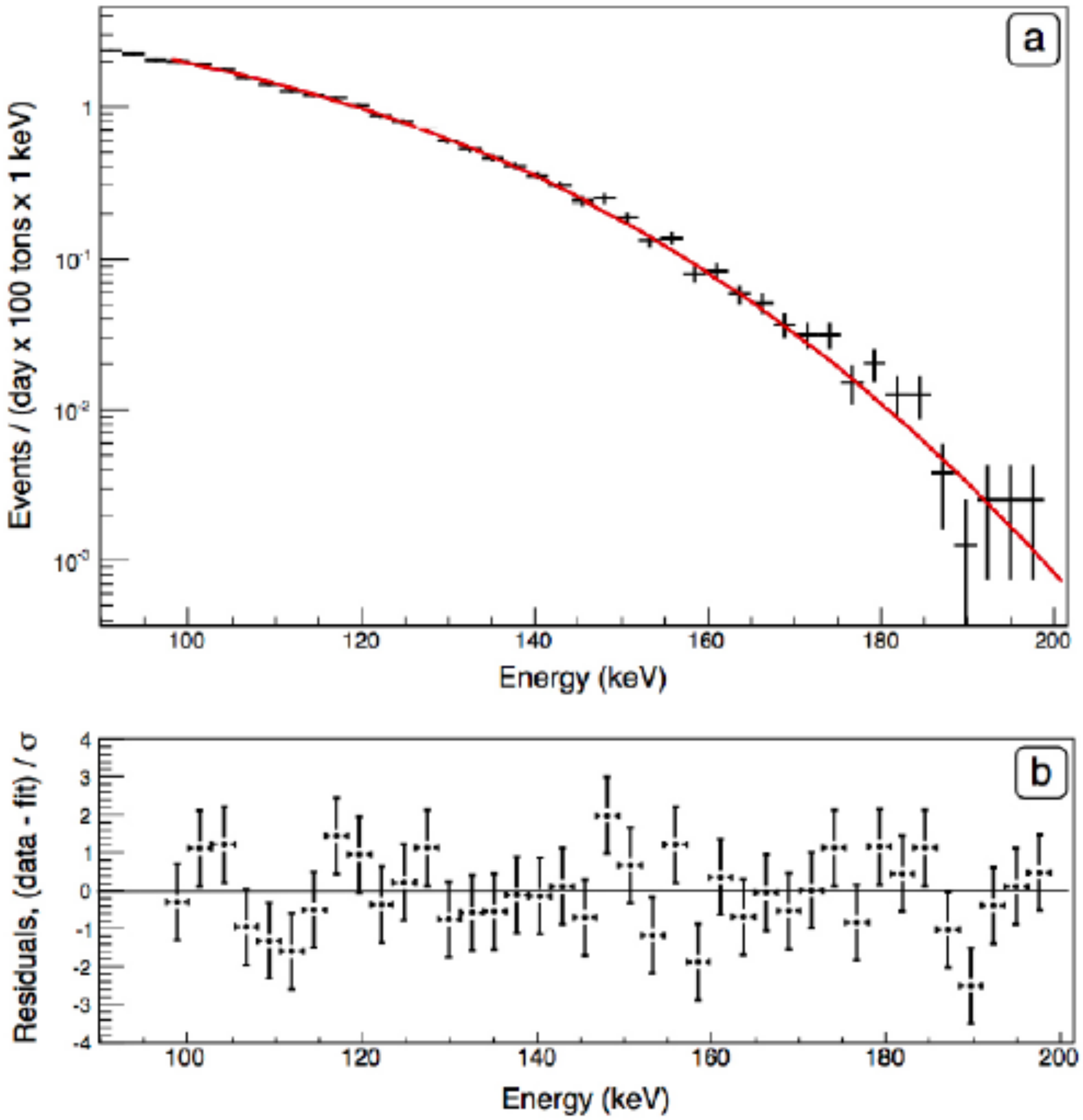




Confirm energy/radial PDF for external bg with high intensity Th-228 source

(arXiv 1110.1217)

^{14}C activity estimation



From 2nd cluster events > 8μs to avoid afterpulses from PMTs

40 ± 1 Bq

$^{14}C/^{12}C = (2.7 \pm 0.1) \times 10^{-18}$

Beta spectrum with shape factor: $1+1.24(Q_\beta-T)$

Nature 512, 383-366 (2014)

^{14}C pile-up

- Rate ^{14}C = 40 Bq
- Cluster window = 230 ns
- Expected pile-up rate ~ 100 cpd/100tons
- Expected pp rate ~ 130 cpd/100tons
- Synthetic pile-up: real triggered events overlapped with random data and processed with reconstruction code: **154 ± 10 cpd/100tons**

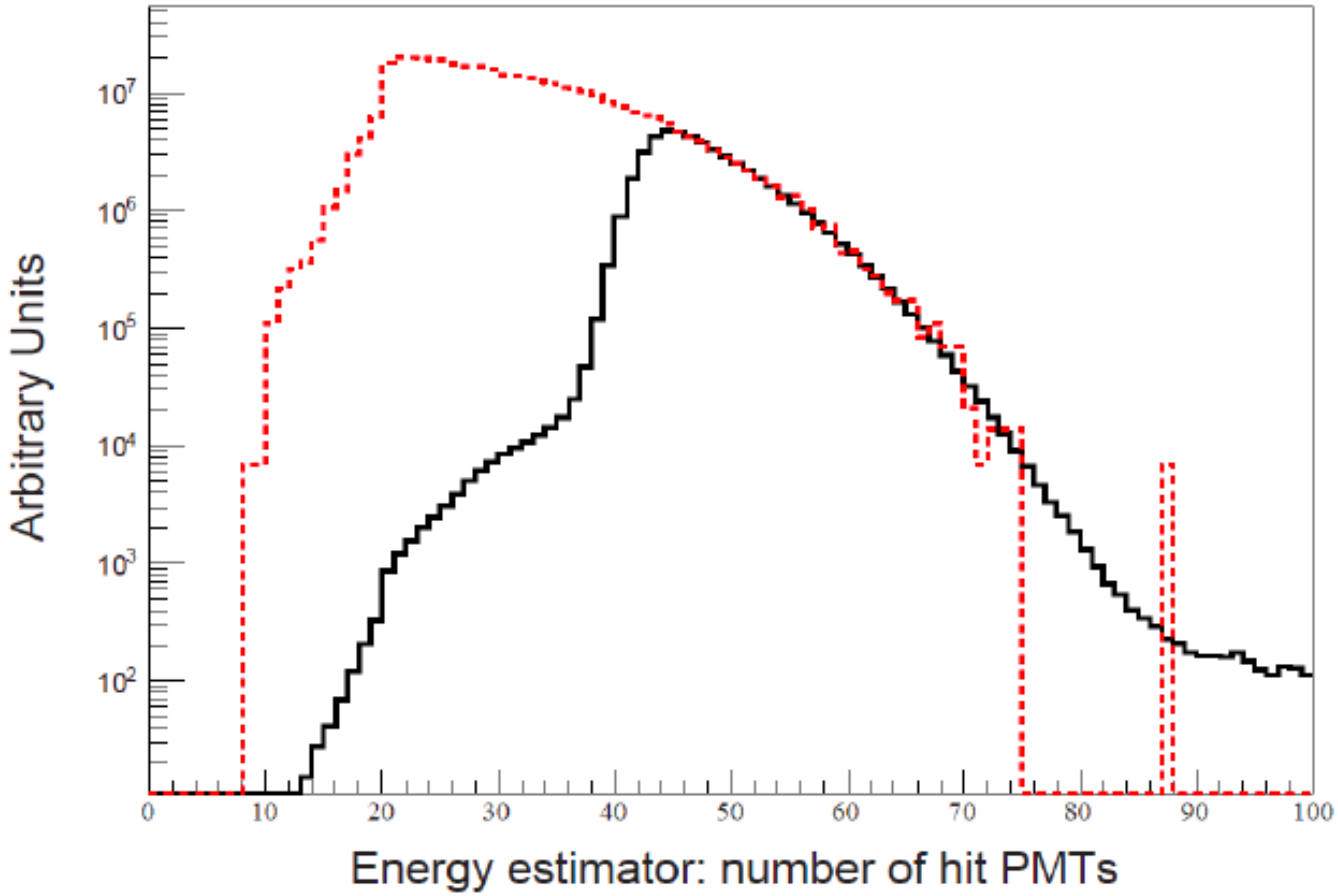
Nature 512, 383-366 (2014)

pp rate result

- Rate-pp = 144 ± 13(stat) ± 10(sys) cpd/100tons
  - Prediction = 131 ± 2 cpd/100tons
- Neutrino flux = $(6.6 \pm 0.7) \times 10^{10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Prediction = $(5.98 \pm 0.04) \times 10^{10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Null hypothesis excluded at 10σ

Nature 512, 383-366 (2014)

^{14}C rate



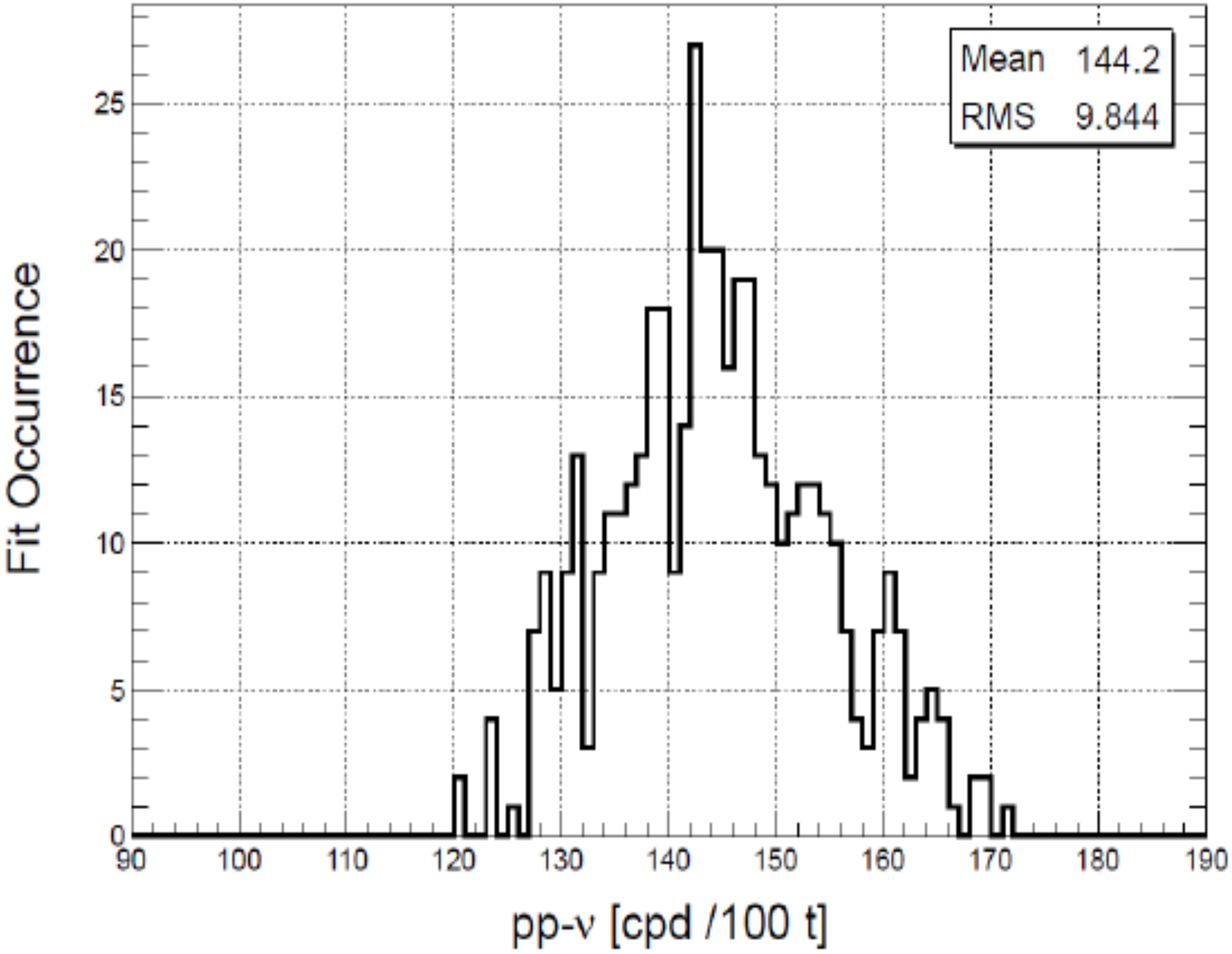
1st cluster with main trigger

2nd cluster events in 16μs with lower threshold

$$N_{PMT} \approx N_{live-PMT}\left(1 - e^{-N_{pe}/N_{live-PMT}}\right)$$

$$N_{pe} = LY \times E \times f(E; k_B)$$

Evaluation of systematic uncertainties



Varying the fit conditions

Perform fit and plot distribution of results for pp rate

Nature 512, 383-366 (2014)

New Purification - CNO neutrinos

- **Goal**: Reduce ^{210}Pb-^{210}Bi-^{210}Po decays by in-line re-purification of scintillator:
  - Reduce rate of ^{210}Bi from 20 cpd/100t to < 2 cpd/100t.
  - Comparable to CNO rate: 3 – 5 cpd/100t

- **Method**:
  - Water extraction with upgraded water radio-purity.
    - LNGS de-ionized water was found to have ^{210}Po and ^{210}Pb
    - Recent research shows that micro-organisms in ground water convert poloniun to volatile compound, dimethyl polonium with B.P. of 138 C.
    - Water extraction plant at LNGS supplemented with distillation column to remove dimethyl polonium
    - Tests done in Princeton had good results

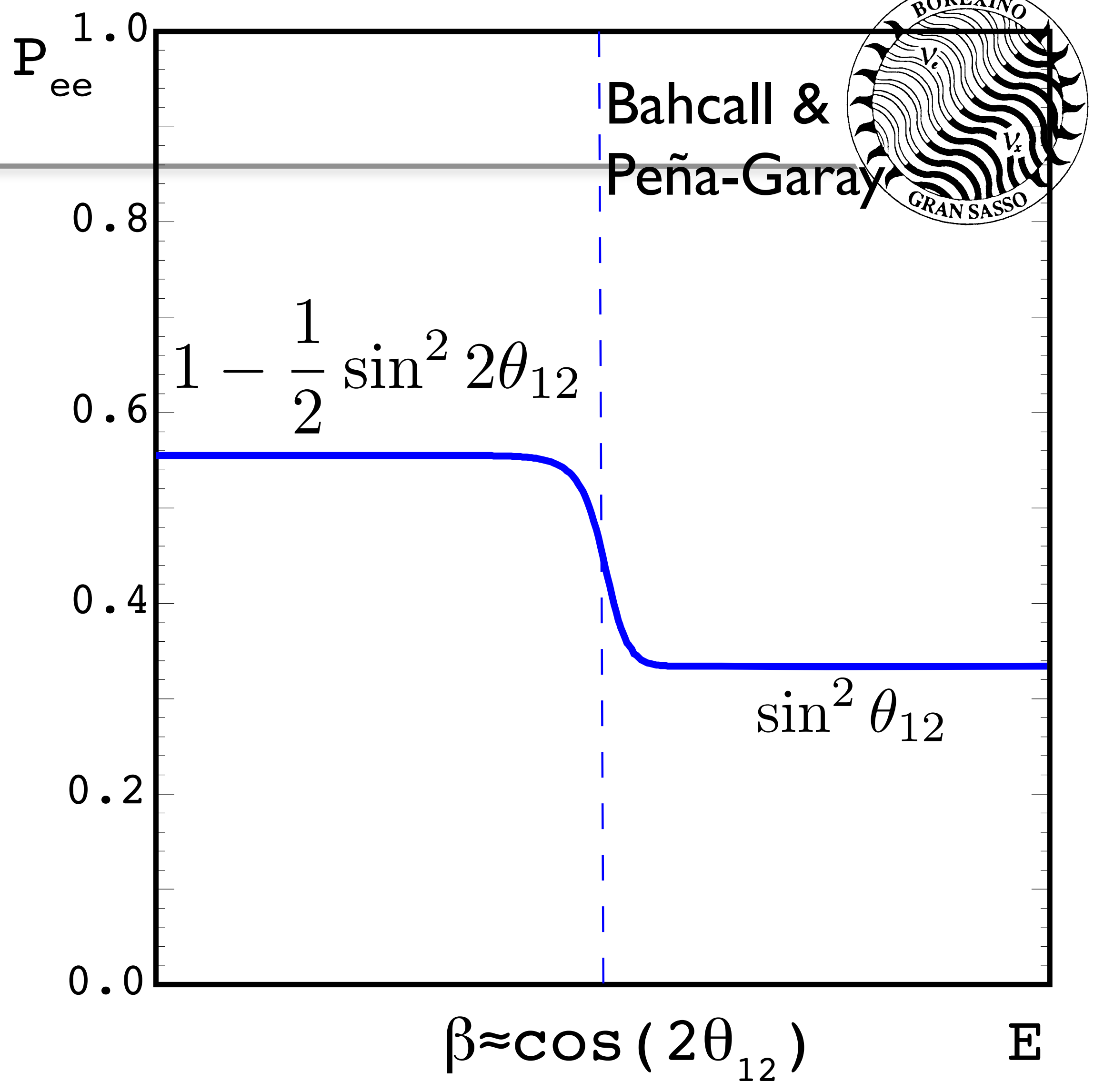
Neutrinos and Solar Metallicity

- A direct measurement of the CNO neutrinos rate could help solve the latest controversy surrounding the Standard Solar Model
- One fundamental input of the Standard Solar Model is the metallicity of the Sun - abundance of all elements above Helium
- The Standard Solar Model, based on the old metallicity derived by Grevesse and Sauval (Space Sci. Rev. **85**, 161 (1998)), is in agreement within 0.5% with the solar sound speed measured by helioseismology.
- Latest work by Asplund, Grevesse and Sauval (Nucl. Phys. A **777**, 1 (2006)) indicates a metallicity lower by a factor ~2. This result destroys the agreement with helioseismology

  maybe it was fortuitous agreement before with high metallicity?
- use solar neutrino measurements to help resolve

  ^{7}Be (12% difference) and CNO (50-60% difference)

neutrino oscillations in matter: MSW effect



$$\begin{pmatrix} -\frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} + \boxed{\sqrt{2}G_F N_e} & \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} \\ \frac{\Delta m^2_{12}}{4E}\sin 2\theta_{12} & \frac{\Delta m^2_{12}}{4E}\cos 2\theta_{12} \end{pmatrix}$$

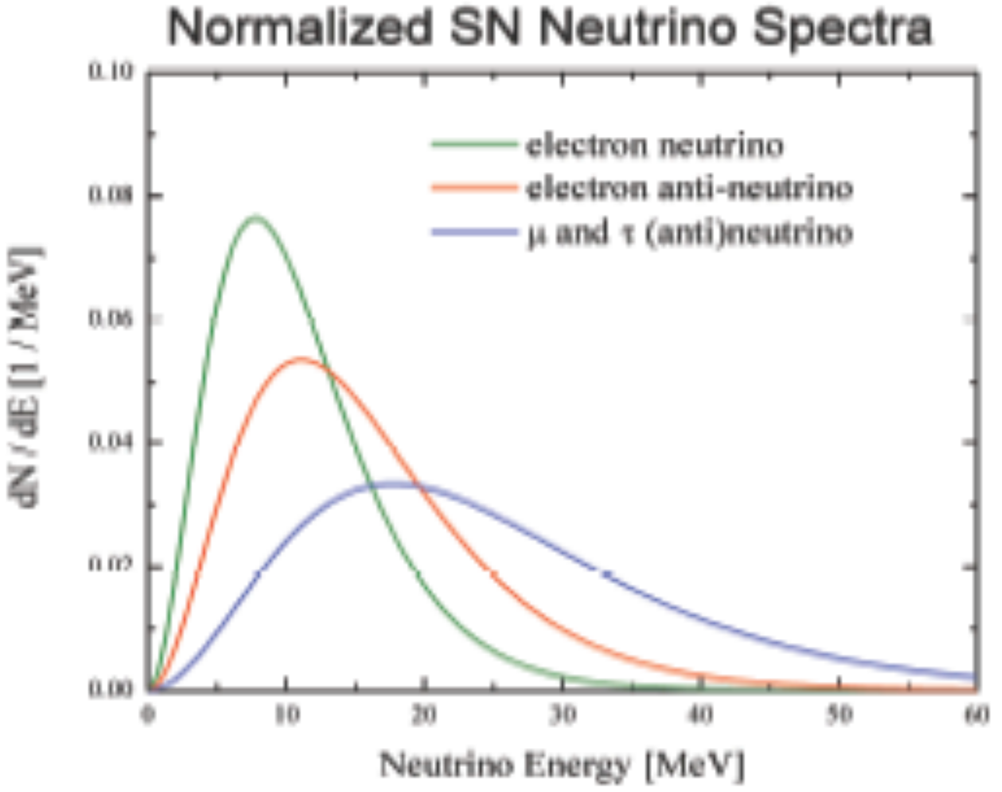
$$\beta = \frac{2^{3/2}G_F N_e E}{\Delta m^2} = 0.22\left[\frac{E}{1\ \mathrm{MeV}}\right]\left[\frac{\rho\cdot Z/A}{100\ \mathrm{g\ cm^{-3}}}\right]\left[\frac{7\times 10^{-5}\ \mathrm{ev}^2}{\Delta m^2}\right]$$

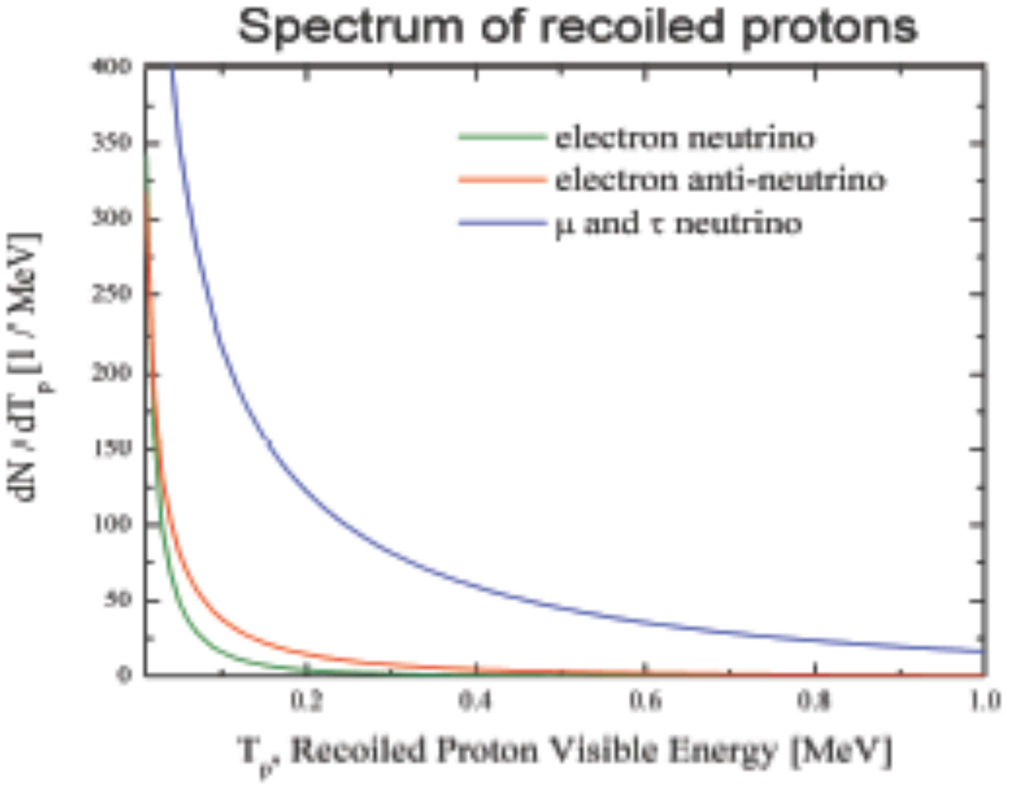
$$P_{ee} = \frac{1}{2} + \frac{1}{2}\cos 2\theta^M_{12}\cos 2\theta_{12} \qquad \cos 2\theta^M_{12} = \frac{\cos 2\theta_{12} - \beta}{\sqrt{(\cos 2\theta_{12} - \beta)^2 + \sin^2 2\theta_{12}}}$$

$$E[\mathrm{MeV}] = 6.8\times 10^6\,\frac{\cos(2\theta_{12})\Delta \mathrm{m}^2_{12}[\mathrm{eV}^2]}{\rho[\mathrm{g/cm}^3]\mathrm{Z/A}} \simeq 1\text{–}2\ \mathrm{MeV}$$

supernova neutrinos

Standard SN @ 10kpc


Normalized SN Neutrino Spectra


Spectrum of recoiled protons

Borexino E_{tresh} = 0.25 MeV
target mass 300 t

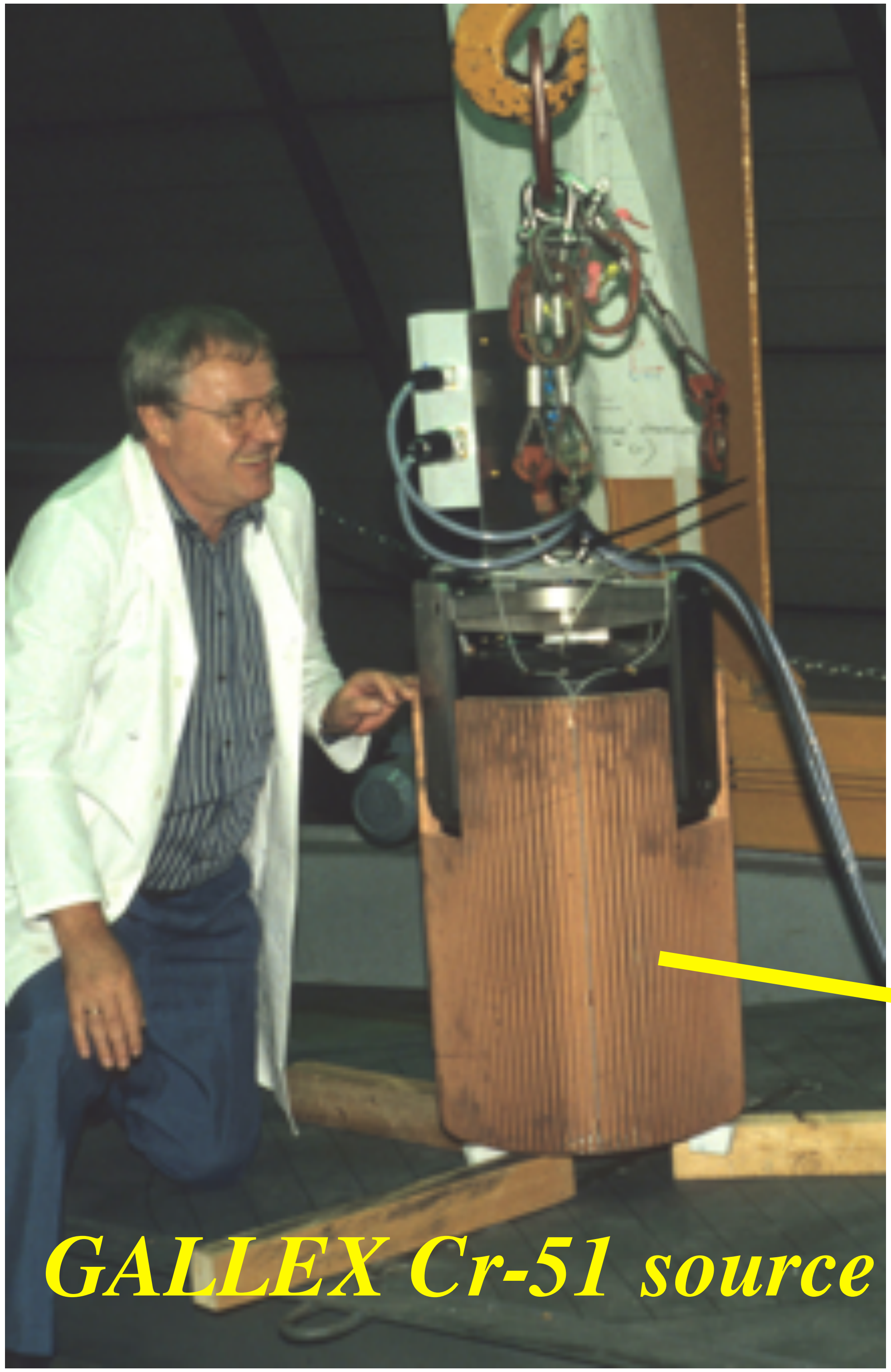
Detection channel	N events
ES ($E_\nu > 0.25$ MeV)	5
Electron anti-neutrinos ($E_\nu > 1.8$ MeV)	78
ν-p ES ($E_\nu > 0.25$ MeV)	52
$^{12}C(\nu,\nu)^{12}C^*$ ($E\gamma = 15.1$ MeV)	18
$^{12}C(\text{anti-}\nu,e^{+})^{12}B$ ($E_{\text{anti-}\nu} > 14.3$ MeV)	3
$^{12}C(\nu,e-)^{12}N$ ($E_\nu > 17.3$ MeV)	9

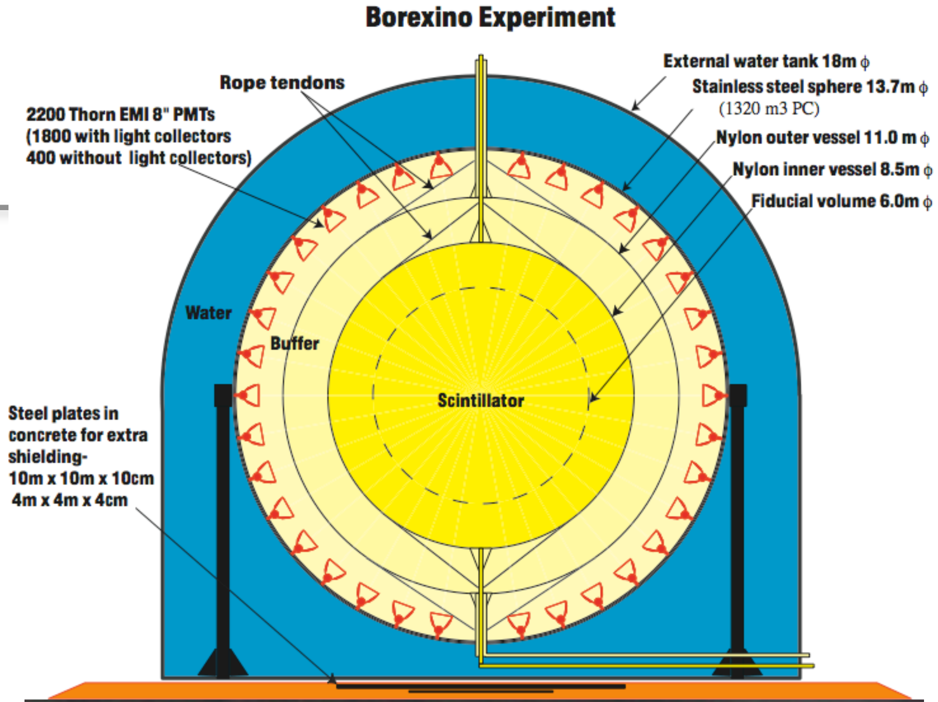
SOX: Short Distance Neutrino Oscillations with BoreXino

- Main focus on ^{144}Ce anti-neutrino source
- Also considering ^{51}Cr neutrino source
- The Cerium Anti Neutrino Generator (**CeANG**) will be manufactured in Russia and will be property of CEA-Saclay

- Probe meter-long neutrino oscillations into sterile neutrinos, corresponding to $\Delta m^2 \sim 1$ eV^2
- Address current 'anomalies' (reactor flux deficit, LSND/MiniBoone)

~MCi source in Borexino





SOX science reach